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Managing Water in the West

Hydraulic Laboratory Report HL-2008-03

Hydraulic Model Study of Arthur R. Bowman Dam Spillway Performance with Proposed Parapet Wall

U.S. Department of the Interior
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A 1:24-scale physical hydraulic model of Arthur R. Bowman Dam was studied at the Bureau of Reclamation's Hydraulics Laboratory. Installation of a 6-ft-high parapet wall on the dam crest has been proposed as part of a flood control alternative at the dam. The model was used to collect rating data to the top of the parapet wall at elevation 3270 ft for both spillway operation and combined spillway and outlet works operation. The model was also used to evaluate the performance of the existing spillway crest structure, spillway chute walls, outlet works, stilling basin, and exit channel during high discharge, low frequency events.

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Hydraulic Laboratory Reports

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Disclaimer

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A 1:24-scale physical hydraulic model of Arthur R. Bowman Dam was used to provide rating data to the top of a proposed 6-ft-high parapet wall (elevation 3270 ft) on the dam crest for operation of the spillway only and combined operation of both the spillway and outlet works flows. The model was also used to evaluate the performance of the existing spillway structure during high discharge, low frequency events.

The spillway structure is an uncontrolled ogee crest with curved inlet walls, a spillway chute, and stilling basin. Controlled by two 4-ft by 6-ft slide gates, the 11-ft-high horseshoe-shaped outlet works conduit releases into a transitional chamber. The outlet works daylight onto the spillway face and share the same stilling basin as the spillway. The design spillway discharge for A.R. Bowman Dam is 8,120 ft^3/s at the design maximum water surface elevation 3257.9 ft. With the current spillway configuration, a discharge of 11,280 ft^3/s for spillway operation only and 14,400 ft^3/s for combined operation will occur at the top of dam elevation 3264 ft. With a 6-ft-high parapet wall to elevation 3270 ft, the discharge is 14,965 ft^3/s for spillway operation and 18,240 ft^3/s for combined operation at reservoir elevation 3269.8 ft.

With a parapet wall installed along the upstream roadway and parking areas, the transition point from free flow to orifice flow occurs around 3269.8 ft, just below the top of the parapet wall at 3270 ft. Once orifice flow initiates, the water surface elevation raises by 4.5 ft. In this model, this happens quickly due to the small size of the model reservoir. In the prototype, the time for the reservoir to rise above the height of the parapet wall may be significant. To prevent chute wall overtopping for discharges corresponding to the top of parapet wall condition, the walls may need to be raised between the break in floor slope and 50 ft downstream of the break in wall slope.

When flows above the design discharge of 8,120 ft^3/s are released through the spillway structure, there are several areas of concern. The hydraulic jump is swept out of the basin for releases above the design discharge under both spillway only operation and combined spillway and outlet works operation. This may produce significant damage to the stilling basin or the area downstream of the basin. The capability of the stilling basin to dissipate energy is exceeded regardless of increased tailwater values. An evaluation of the condition of the rock downstream from the stilling basin should be conducted with a risk assessment to determine if undermining of the stilling basin could cause dam failure.

Introduction

A 1:24-scale physical hydraulic model of Arthur R. Bowman Dam was constructed at the Bureau of Reclamation's (Reclamation) Hydraulics Laboratory in Denver, Colorado in July 2003. A.R. Bowman Dam (formerly Prineville Dam) is an earthfill structure on the Crooked River about 20 miles upstream from Prineville, Oregon (figure 1). The dam has a height of 245 feet, crest length of 800 feet, and a volume of 1,424,000 cubic yards of material. Prineville Reservoir has an active capacity of 152,800 acre-feet and a surface area of 3,030 acres at the spillway crest elevation 3234.8 ft (United States Department of the Interior, 1981). Figure 2 shows an aerial view of A.R. Bowman Dam.

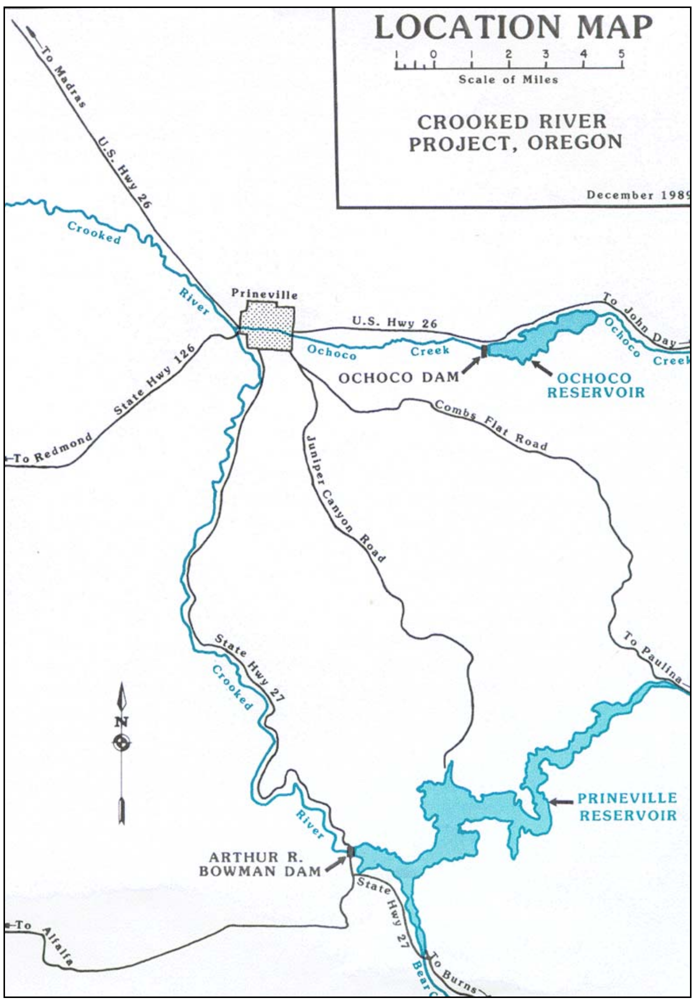

Figure 1 – Location map of Arthur R. Bowman Dam.

Figure 2 – Aerial view of A.R. Bowman Dam looking downstream with the existing spillway on the right abutment.

The spillway structure is an uncontrolled ogee crest with curved inlet walls, a spillway chute, and a stilling basin. At the design maximum water surface elevation 3257.9 ft, the capacity of the spillway is 8,120 ft^3/s. The outlet works consist of an 11-foot-diameter circular tunnel upstream from the gate chamber, two 4-ft by 6-ft slide gates, and an 11-foot horseshoe-shaped tunnel downstream from the gate chamber. The capacity of the outlet works is 2,900 ft^3/s with a maximum gate opening of 5.5 ft at the top of the spillway crest (elevation 3234.8 ft).

Flow from the outlet works daylights onto the spillway face and enters the shared stilling basin. Two splitter walls are constructed in the stilling basin on both sides of the outlet works opening to prevent flow attachment to the basin sidewalls and to improve flow conditions in the stilling basin when the outlet works are operating. In the event of a flood, outlet works releases will be ramped down as spillway flows increase such that the total combined release does not exceed the safe channel capacity of 3,000 ft^3/s. The outlet works will be fully reopened if the safety of the dam is at risk.

For large storm events exceeding the capacity of the existing spillway structure, analyses have indicated that a combination of changing operational procedures and installing a parapet wall on the dam crest do not sufficiently reduce risk to downstream populations according to Reclamation's guidelines (Reclamation, 2007). For this reason, additional corrective action alternatives that would safely pass inflow floods with a return period of 100,000 years are currently under consideration (Reclamation, 2008).

The physical model was used to provide rating data for spillway operation, combined spillway and outlet works operation, and a parapet wall flood control alternative for the flood hydrology analysis and risk assessment in 2004. The hydraulic model was employed again in 2007 to evaluate the performance of the existing spillway structure for reservoir elevations up to the top of a 6-ft-parapet wall at 3270 ft.

Model Description

The physical model was built at a 1:24 scale with Froude-based similitude. The lateral extent of the model includes about 1/3 of the length of the dam on the right side. Concrete topography was installed 240 ft upstream of the dam crest in the headbox and 650 ft downstream of the toe of the dam in the tailbox. Figures 3 and 4 compare the prototype and model structures.

Upstream features include the concrete approach channel, high-density polyurethane foam spillway crest, sheet metal curved inlet structures, and a plywood roadway and parapet wall (figure 5). A 6-ft parapet wall was installed along the upstream side of the roadway, around the curved inlet structures, and above the spillway chute inlet. The marine-grade plywood spillway chute flares from 20 ft wide at the spillway crest to 54 ft in the stilling basin (figure 6).

The horseshoe-shaped outlet works tunnel, two 4 ft by 6 ft slide gates, and the transition chamber were constructed of clear acrylic (figure 7). A clear acrylic viewing area was installed next to the transition chamber in order to observe flow patterns in the region where the outlet works daylight onto the spillway face. Stilling basin details included chute blocks, dentated endsill, and two splitter walls (figure 8).

Inflow to the hydraulic model was measured by the calibrated laboratory venturi system. Reservoir and tailwater elevations were measured with point gages inside stilling wells in the headbox and tailbox. Vertical slats at the downstream end of the model were used to adjust the tailwater elevation in the model.

Figure 3 – A.R. Bowman prototype spillway structure.

Figure 4 – A.R. Bowman model spillway structure.

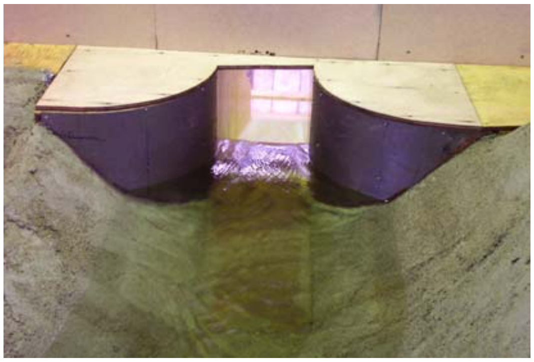

Figure 5 – Spillway crest structure.

Figure 7 – Outlet works tunnel.

Figure 6 – Spillway chute.

Figure 8 – Stilling basin configuration.

Test Plan

Model testing was performed during the following operational scenarios:

1.) Spillway operation only

2.) Outlet works operation only

3.) Combined spillway and outlet works operation.

Discharge rating data were collected up to the top of parapet wall elevation of 3270 ft. Flow conditions were documented using a digital camera and video camera for critical flow rates and water surface elevations. Model observations included:

- Reservoir conditions and spillway inlet flow patterns
- Transition point between free flow and orifice flow
- Spillway chute flow depths
- Outlet works tunnel and chamber flow conditions
- Combined outlet works and spillway flow patterns

- Stilling basin performance
- Hydraulic jump location and strength
- Exit channel flow conditions and downstream erosion potential
- Stilling basin and exit channel conditions under increased tailwater that may occur if an auxiliary spillway structure is constructed

Results

Discharge Ratings

Spillway Operation Only

A rating curve was developed for spillway operation up to the top of the parapet wall at elevation 3270 ft (figure 9). The spillway begins discharging when the reservoir water surface elevation exceeds the spillway crest elevation of 3234.8 ft. The spillway capacity is 8,120 ft^3/s at the design maximum water surface elevation of 3257.9 ft. The spillway flow is 11,280 ft^3/s at the elevation of the top of dam at 3264 ft. As the reservoir water surface increases local drawdown occurs under the roadway, still producing free flow through the spillway.

At reservoir elevation 3269.8 ft, free flow is no longer maintained through the spillway and orifice flow begins as the flow is closed off on the bottom of the roadway. During the transition from free flow to orifice flow, the water surface elevation rises by 4.5 ft, until the water surface exceeds the parapet wall height. This sudden increase in water surface elevation could be a function of the relatively small model reservoir area and would not occur as quickly in the prototype. However, the model does not include wave action that would most likely occur in the prototype during a large storm event. Wave action may also trigger the orifice flow condition.

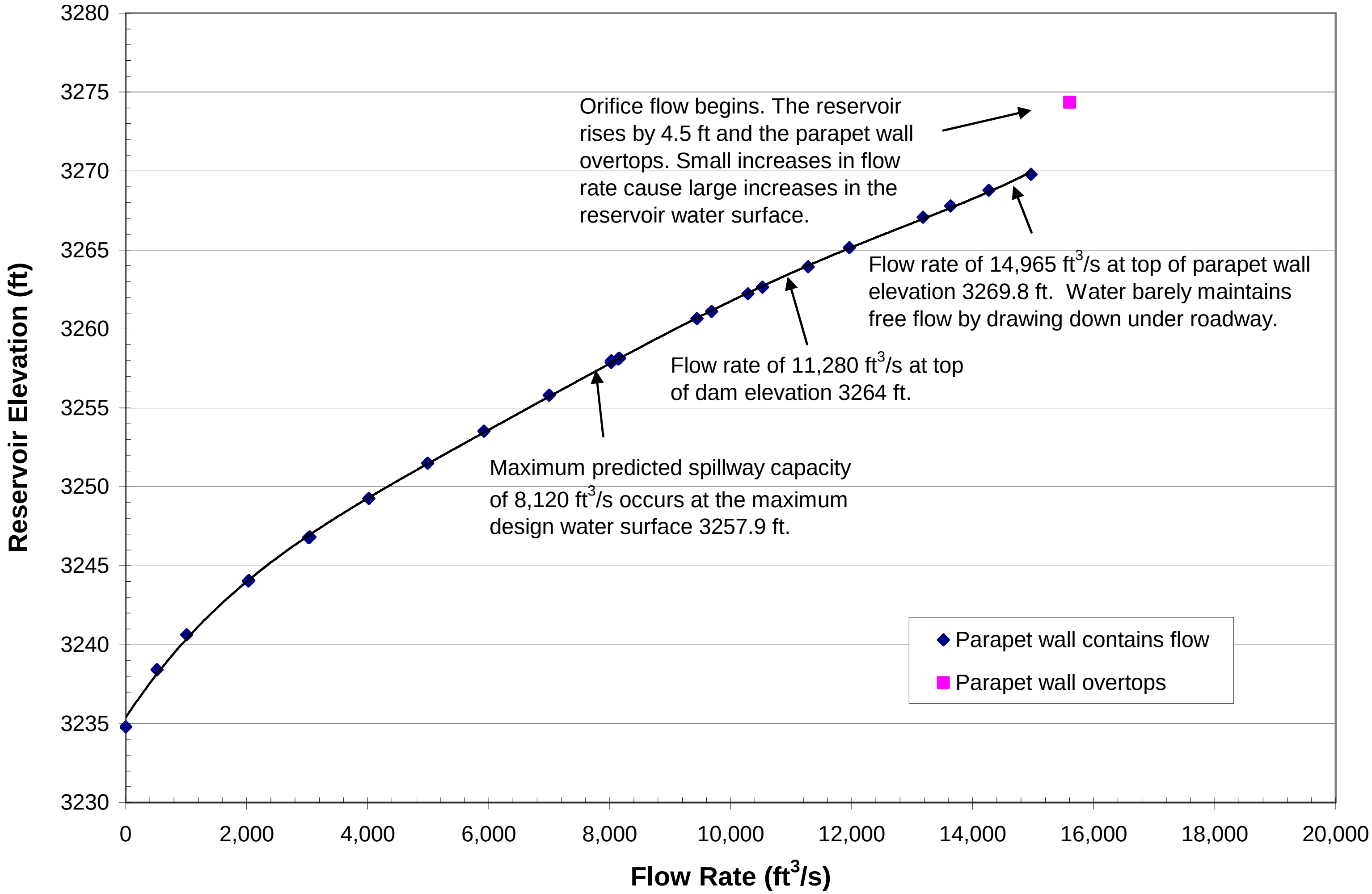

Figure 9 – Discharge curve for spillway operation only with a 6-ft parapet wall installed to elevation 3270 ft.

Combined Spillway and Outlet Works Operation

A rating curve was also developed for combined spillway and outlet works operations up to the top of the parapet wall at elevation 3270 ft (figure 10). The outlet works capacity is 2,900 ft^3/s with gates set to the restricted maximum opening of 5.5 ft at the spillway crest elevation of 3234.8 ft. With combined operation of the spillway and outlet works, the spillway capacity of 8,120 ft^3/s occurs at a water surface elevation of 3251.8 ft rather than the design value of 3257.9 ft with spillway only flow. The combined flow is 14,400 ft^3/s at the top of dam elevation 3264 ft. Like the spillway only condition, water continues to draw down through the spillway under the roadway until elevation 3269.8 ft, correlating to a discharge of 18,240 ft^3/s. At this water surface elevation, orifice flow begins and the reservoir water surface exceeds the height of the parapet wall.

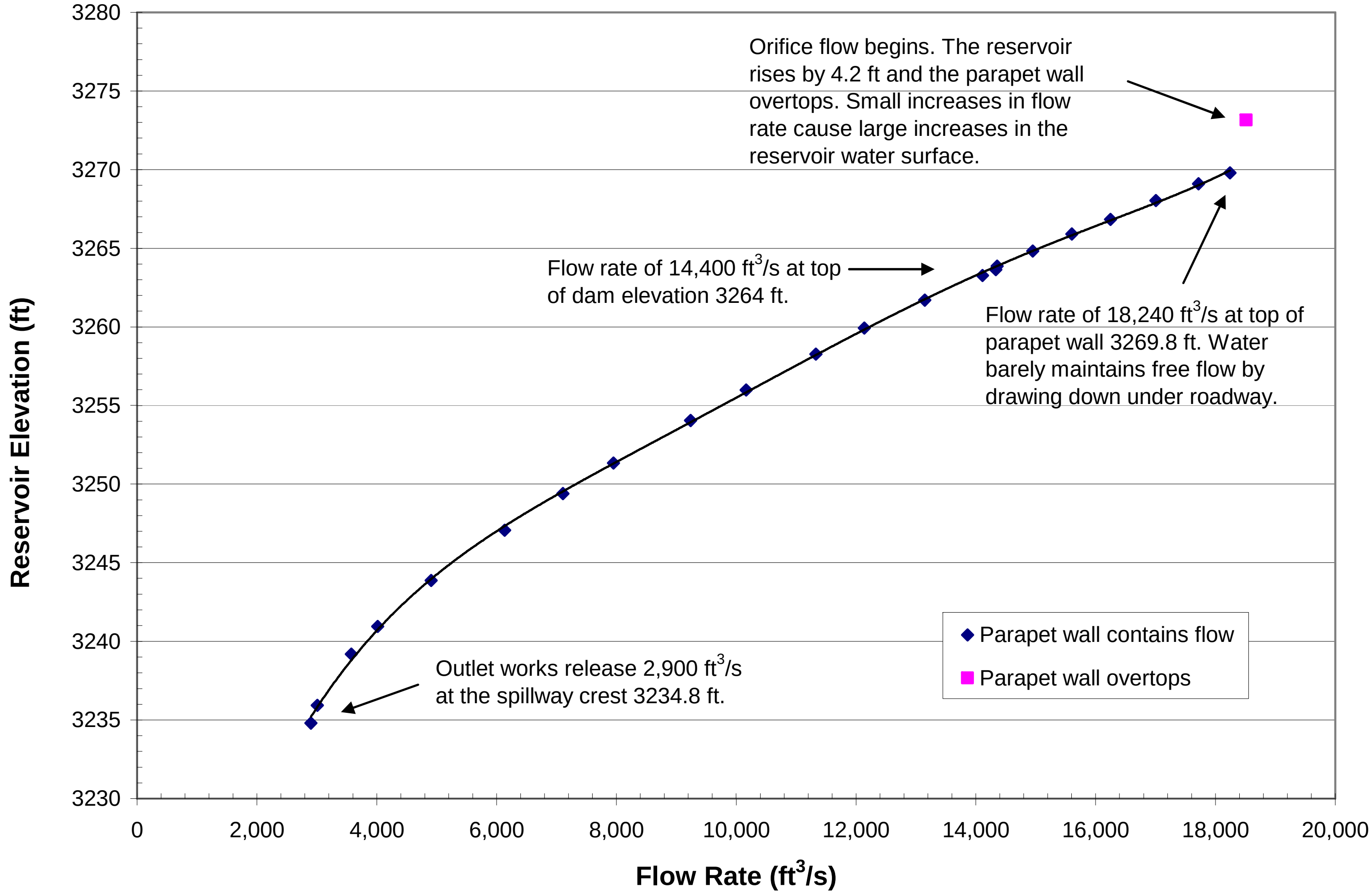

Figure 10 – Discharge rating curve for combined spillway and outlet works operation with a 6-ft parapet wall installed to elevation 3270 ft.

Performance Observations

Model testing was performed under three operational scenarios: spillway operation only, outlet works operation only, and combined spillway and outlet works operation. During these scenarios, model observations were recorded for various flow conditions including a maximum outlet works release of 2,900 ft^3/s, channel capacity of 3,000 ft^3/s, design spillway discharge of 8,120 ft^3/s, and flow rates corresponding to the top of dam at elevation 3264 ft and top of parapet wall elevation at 3270 ft. A summary of observations is presented in the sections below. Full observation tables are located in Appendix 1.

Reservoir Conditions

For water surface elevations at and above the top of dam (3264 ft), flow separates off the sharp parapet wall corner on top of the left inlet structure and produces a flow disturbance (figure 11). The wave bulks the flow on the left side of the spillway, forcing water up onto the roadway parapet wall while water continues to free flow on the right side. Adding a curve to the sharp corner would improve flow conditions, may increase the capacity of the spillway, and may prevent early transitioning to orifice flow.

Figure 11 – At a reservoir elevation near 3270 ft, flow separation off of the left parapet wall corner produces a higher water surface on the left side of the spillway crest.

Spillway Chute Wall Flow Profiles

Water depths were measured vertically at 10 locations in the spillway chute during high flow conditions. To compare water depths in the spillway between the model and prototype, flow bulking must be considered. One-third of the water depth was added to the measured water depth to account for flow bulking (Wood, 1983).

Chute wall overtopping potential appears minimal for spillway discharges up to the top of dam elevation 3264 ft. However, the chute walls may overtop for releases at the top of parapet elevation 3270 ft. The break in floor slope from 0.31 to 0.40 at Sta. 9+22.32 causes an undulation in the water surface. At this location, the freeboard is approximately 1.25 ft for spillway only operation and 1.6 ft for combined operation with flow bulking included. At Sta 9+70.00, the chute wall slope changes from 0.5 to 0.41858. From the break in chute wall slope to about 50 ft downstream of the slope change, the water surface is less than 1 ft prototype from the top of the wall with bulking considered. Chute wall locations upstream and downstream of this region are sufficient for containing the flow for high discharge events.

Figures 12 and 13 illustrate the locations where additional wall height may be needed to prevent overtopping during large releases. Tables 1 and 2 and figures 14 and 15 show results from chute wall model testing.

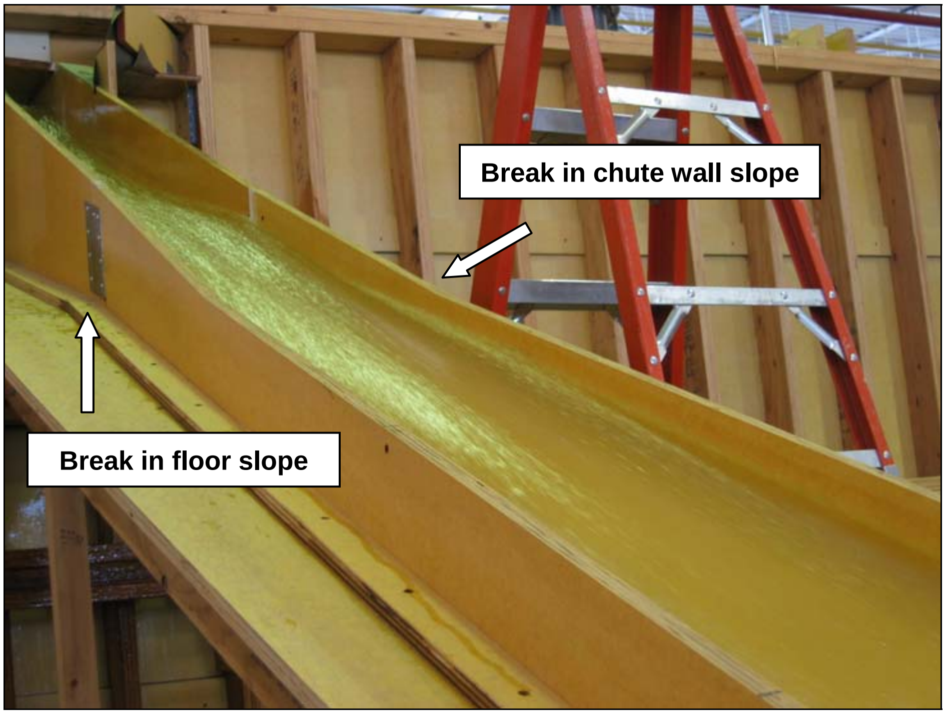

Figure 12 – The break in floor slope and break in chute wall slope produce the least amount of freeboard in the chute. This photograph was taken during combined operations at reservoir elevation 3270 ft.

Figure 13 – For the same condition, wall heights are adequate in containing high discharge events in the downstream section of the chute.

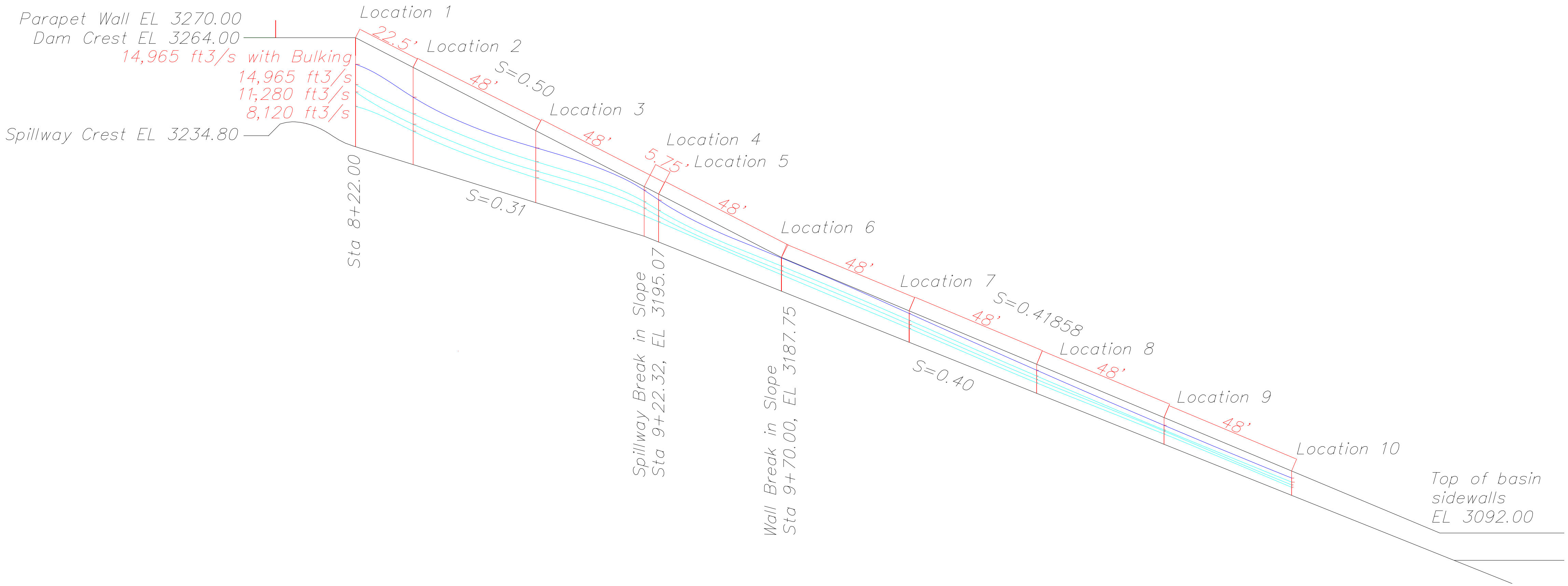

Figure 14 – Water surface profiles in the spillway chute for spillway only flow. Estimated bulking was added in for the discharge relating to the top of parapet wall condition at elevation 3270 ft.

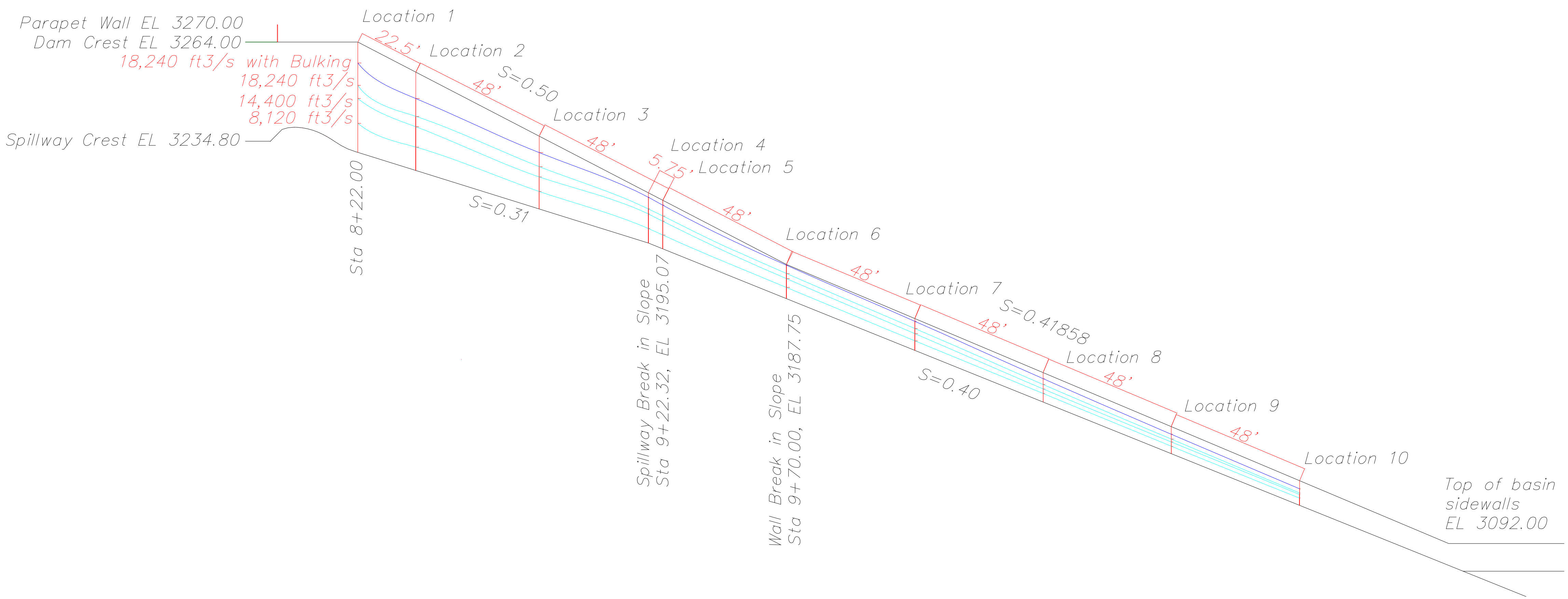

Figure 15 – Water surface profiles in the spillway chute for combined spillway and outlet works flows. Estimated bulking was added in for the discharge relating to the top of parapet wall condition at elevation 3270 ft.

Table 1 – Prototype water depths measured vertically in the spillway chute for spillway only operation.

	Water Depth (ft)			Water Depth with 1/3 Bulking Depth (ft)			Approximate Wall Height at Data Location (ft)	Freeboard to Top of Chute Wall (ft)
	8,120 ft^3/s	11,280 ft^3/s	14,965 ft^3/s	8,120 ft^3/s	11,280 ft^3/s	14,965 ft^3/s		
	EL 3257.9	EL 3264	EL 3270	EL 3257.9	EL 3264	EL 3270		
Location 1	14	19	21.5	18.7	25.3	28.7	37.9	9.2
Location 2	11.5	14	17.5	15.3	18.7	23.3	33.8	10.4
Location 3	8.5	11	14.3	11.3	14.7	19.0	25.0	6.0
Location 4	7.3	9.8	12	9.7	13.0	16	17.3	1.3
Location 5	7	9	11	9.3	12	14.7	16.6	2.0
Location 6	5.5	7	8.5	7.3	9.3	11.3	11.6	0.3
Location 7	4.8	6.3	7.5	6.3	8.3	10	11.0	1.0
Location 8	3.5	4.8	6	4.7	6.3	8	10.1	2.1
Location 9	3.5	4.5	5	4.7	6	6.7	9.4	2.7
Location 10	2.8	3.5	4.5	3.7	4.7	6	8.4	2.4

Table 2 – Prototype water depths measured vertically in the spillway chute for combined spillway and outlet works operation.

	Water Depth (ft)			Water Depth with 1/3 Bulking Depth (ft)			Approximate Wall Height at Data Location (ft)	Freeboard to Top of Chute Wall (ft)
	8,120 ft^3/s	14,400 ft^3/s	18,240 ft^3/s	8,120 ft^3/s	14,400 ft^3/s	18,240 ft^3/s		
	EL 3251.8	EL 3264	EL 3270	EL 3251.8	EL 3264	EL 3270		
Location 1	10	18.5	23	13.3	24.7	30.7	37.9	7.2
Location 2	8	15	18.5	10.7	20	24.7	33.8	9.1
Location 3	6	11	14.5	8	14.7	19.3	25.0	5.7
Location 4	5	10	11.8	6.7	13.3	15.7	17.3	1.6
Location 5	4.8	9.5	11.3	6.3	12.7	15.0	16.6	1.6
Location 6	3.8	6.8	8.5	5.0	9.0	11.3	11.6	0.3
Location 7	3.3	5.8	7.5	4.3	7.7	10.0	11.0	1.0
Location 8	3	4.5	6	4	6	8.0	10.1	2.1
Location 9	2.5	4	5	3.3	5.3	6.7	9.4	2.7
Location 10	2.5	3.8	4.3	3.3	5.0	5.7	8.4	2.7

Outlet Works Conditions

The outlet works represented in the model consist of two 4-ft by 6-ft slide gates and 357 ft of an 11-foot horseshoe-shaped tunnel downstream from the gate chamber. Outlet works flow enters a transitional chamber before daylighting onto spillway face (figure 16).

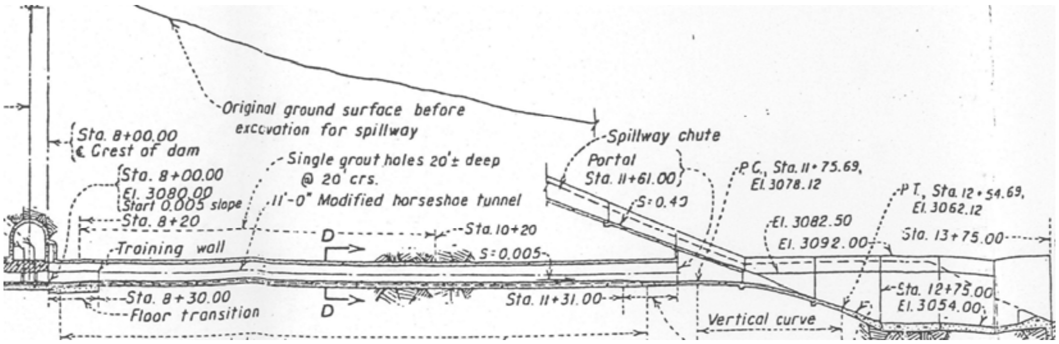

Figure 16 – Original model drawing showing the configuration of the outlet works and transitional chamber.

A full-height splitter wall was installed in the model along the centerline of the outlet works tunnel from the end of a short training wall downstream of the gate chamber to the start of the transitional chamber. In the chamber, the splitter wall tapered from the end of the conduit to the top lip of the spillway opening. The splitter wall installation was part of a concurrent study to determine if a splitter wall could be used to allow operation and maintenance activities on either side of the tunnel while meeting the minimum bypass flow requirements for downstream fish and habitat. In 2006, a 4-ft-high splitter wall was constructed inside the outlet works tunnel in the prototype.

Outlet works model observations were noted with spillway flow only, outlet works flow only, and combined spillway and outlet works operation. When the outlet works are closed, spillway flow does not enter the outlet works transition chamber for flows less than 11,280 ft^3/s. At a spillway flow of 11,280 ft^3/s, water surges about halfway into the transitional chamber and at 14,965 ft^3/s, water surges to the upstream end of the transition chamber. When the outlet works are operating at the restricted maximum gate opening of 5.5 ft, the water depth inside the conduit is approximately 5 ft (figure 17) and flow through the transitional chamber is below the top of the splitter wall. When outlet works and spillway flows are released simultaneously, spillway flow is not drawn into the outlet works chamber during any tested flow condition (figure 18).

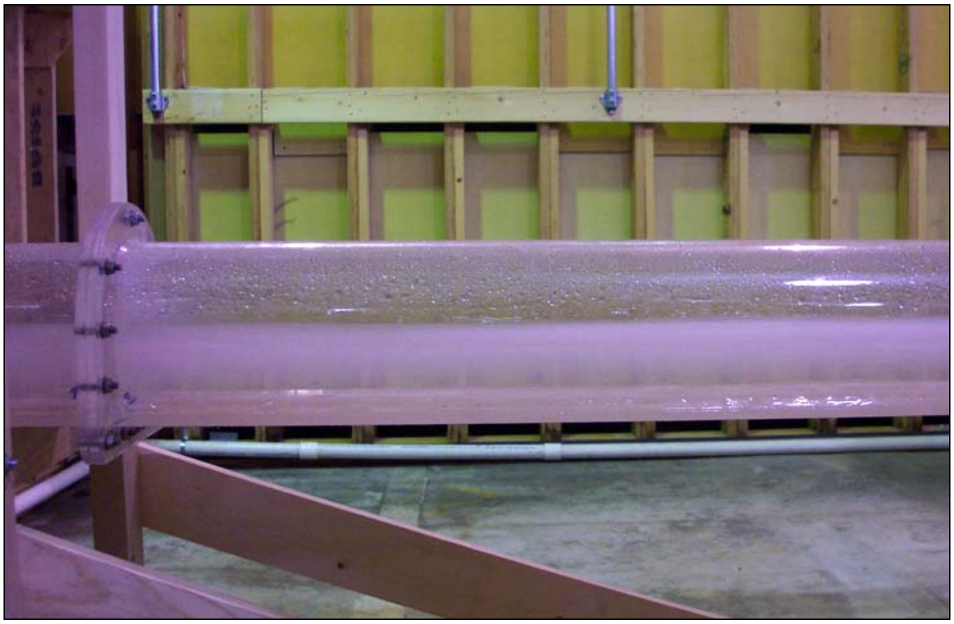

Figure 17 – Outlet works release with water depth of approximately 5 ft.

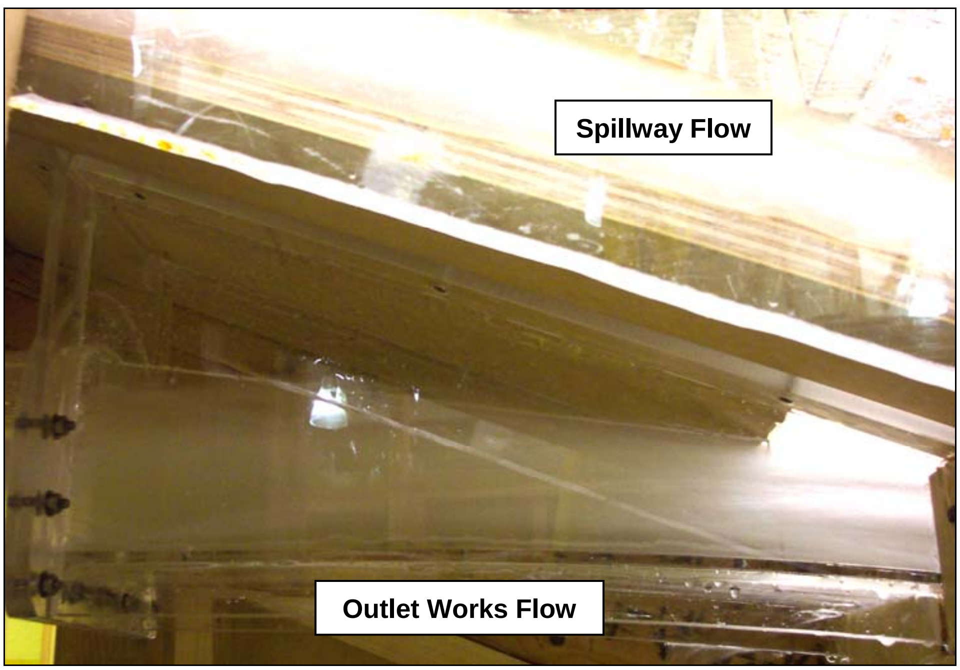

Figure 18 – Transition chamber at the end of the outlet works tunnel with combined flow.

Stilling Basin and Exit Channel Flow Conditions

Stilling basin model observations were investigated with spillway flow only, outlet works flow only, and combined spillway and outlet works operation. Observations were made under channel capacity and existing design flow rates.

Flows were then increased up to those that would be experienced under reservoir elevation 3270 ft with a 6-ft-high parapet wall. For flow conditions when the hydraulic jump is swept out of the basin and strong turbulence extends downstream of the basin, erosion damage or rock jacking may be a concern. High velocity flow, strong wave action against the right bank, and recirculation behind the left basin wall may cause erosive forces.

For spillway only releases, the stilling basin contains the hydraulic jump for the channel capacity flow of 3,000 ft^3/s. The hydraulic jump occurs above the endsill during the design flow of 8,120 ft^3/s producing a boil that extends 4-6 ft above the normal water surface and spreads 24-32 ft downstream of the basin (figure 19). At 11,280 ft^3/s, the hydraulic jump sweeps out of the basin producing a large boil that extends 6-8 ft above the normal water surface and 40-48 ft downstream of the endsill. Lateral spreading produces strong wave action against the right bank (figure 20). At 14,965 ft^3/s, the boil extends 8-10 ft above the normal water surface and about 64 ft downstream of the endsill with strong wave action against the right bank (figure 21).

During spillway only operation, flow is evenly spread across the width of the basin, but the water depth is shallow in the upstream section of the basin when the hydraulic jump is swept downstream. For high flows, the water depth increases with distance downstream, such that it nears the top of wall by the end of the basin and splashes up over the basin walls. At 11,280 ft^3/s and above, some surging over the basin sidewalls occurs, but not as much as with combined outlet works flows. By 14,965 ft^3/s, strong reverse flow occurs toward spillway face due to the downstream boil, causing notable splitter wall vibration. This may be a function of the model construction materials, but could produce additional or unexpected loading on the existing stilling basin splitter walls. The tailwater is at the top of outside basin walls.

Figure 19 – Spillway only release of 8,120 ft^3/s at reservoir elevation 3257.9 ft.

Figure 20 – Spillway only release of 11,280 ft^3/s at reservoir elevation 3264 ft.

Figure 21 – Spillway only release of 14,965 ft^3/s at reservoir elevation 3269.8 ft.

For the outlet works only condition at a maximum release of 2,900 ft^3/s, flow is released in the center section of the stilling basin between the splitter walls (figure 22). Turbulence is well contained within the stilling basin.

Figure 22 – Outlet works only release of 2,900 ft^3/s at spillway crest elevation 3234.8 ft.

During combined spillway and outlet works releases, the impact of the outlet flow in the basin causes more turbulence and flow surging than for the spillway only release condition. Since the outlet works release in the center of the basin pushes the hydraulic jump farther downstream, water depths on the right and left sides of the splitter walls at the upstream end of the basin are up to about 10 ft higher than in the center. For flows above 8,120 ft^3/s, water from the right and left sides of the basin overtop the splitter walls and enter the center portion of the basin. At 8,120 ft^3/s, there is occasional surging over the basin sidewalls. Flow surges of 12-18 ft and 18-24 ft above the average water surface occur regularly at 14,400 ft^3/s and 18,240 ft^3/s, respectively.

The stilling basin contains the hydraulic jump for the channel capacity flow of 3,000 ft^3/s. At the design discharge of 8,120 ft^3/s with a combined release, the hydraulic jump initiates at the endsill with a boil extending about 48 ft downstream of the basin (figure 23). At 14,400 ft^3/s, the turbulent boil extends about 6-8 ft above the normal water surface and 72 ft downstream of the basin (figure 24). At 18,240 ft^3/s, the turbulent boil extends about 10-12 ft above the normal water surface and 84 ft downstream of the basin (figure 25). For both high flow scenarios, the boil spreads strongly in the lateral direction, producing strong wave action against the right bank and a recirculating eddy behind the left basin wall. There is strong reverse flow toward the spillway face due to the downstream boil. Notable splitter wall vibration occurs at 14,400 ft^3/s. Significant splitter wall vibration occurs at 18,240 ft^3/s. The tailwater is higher than the stilling basin walls, so water overtops the basin walls, producing excessive turbulence.

Figure 23 – Combined release of 8,120 ft^3/s under reservoir elevation 3251.8 ft.

Figure 24 – Combined release of 14,400 ft^3/s under reservoir elevation 3264 ft.

Figure 25 – Combined release of 18,240 ft^3/s under reservoir elevation 3269.8 ft.

Tailwater Effects

As the spillway and outlet works discharges exceed the original design capacity of the existing spillway structure, the hydraulic jump cannot be contained in the stilling basin with the corresponding tailwater. If an auxiliary spillway structure is chosen as the corrective action at A.R. Bowman Dam, the anticipated tailwater will increase downstream of the dam during high flow events. The performance of the existing stilling basin was reevaluated with the reservoir water surface level at the top of the parapet wall (elevation 3270 ft). Tailwater was increased to elevation 3094.5 ft corresponding to a 25,000 ft^3/s event and 3097.8 ft corresponding to a 35,000 ft^3/s event.

With the tailwater corresponding to the 25,000 ft^3/s total flow event, water pours over the basin sidewalls causing continual splashing (figure 26). The hydraulic jump initiates at about the same location as with the lower tailwater condition. With spillway flow only, there is some reverse flow toward the spillway face due to downstream boil, causing noticeable vibration of the splitter walls. With a combined release, there is strong reverse flow, causing violent vibration of splitter walls. In both release scenarios, the hydraulic jump extends about as far downstream as it did without increased tailwater, but the height of the boil is reduced by about 2-4 ft and there is noticeably less turbulence in the basin and downstream. The recirculating eddy behind the left basin wall is drowned out, but wave action against the right bank is still very strong.

With the tailwater corresponding to the 35,000 ft^3/s total flow event, the water inside and outside of the basin are at the same height in the downstream third of the basin (figure 27). Water pours over the basin sidewalls in the first two-thirds of the basin causing continual splashing. The splitter walls are completely submerged except at the location of the initiation of the jump. As the tailwater drowns out the boil, the length of the hydraulic jump extends by about 16 ft, but the height of the boil is reduced by about 6-8 ft. All recirculation areas are drowned out, and the waves splashing against the right bank are higher than the top of the model topography at elevation 3105 ft.

Figure 26 – Performance of stilling basin with a tailwater equivalent to a 25,000 ft^3/s release. A combined release of 18,240 ft^3/s under reservoir elevation 3269.8 ft is shown.

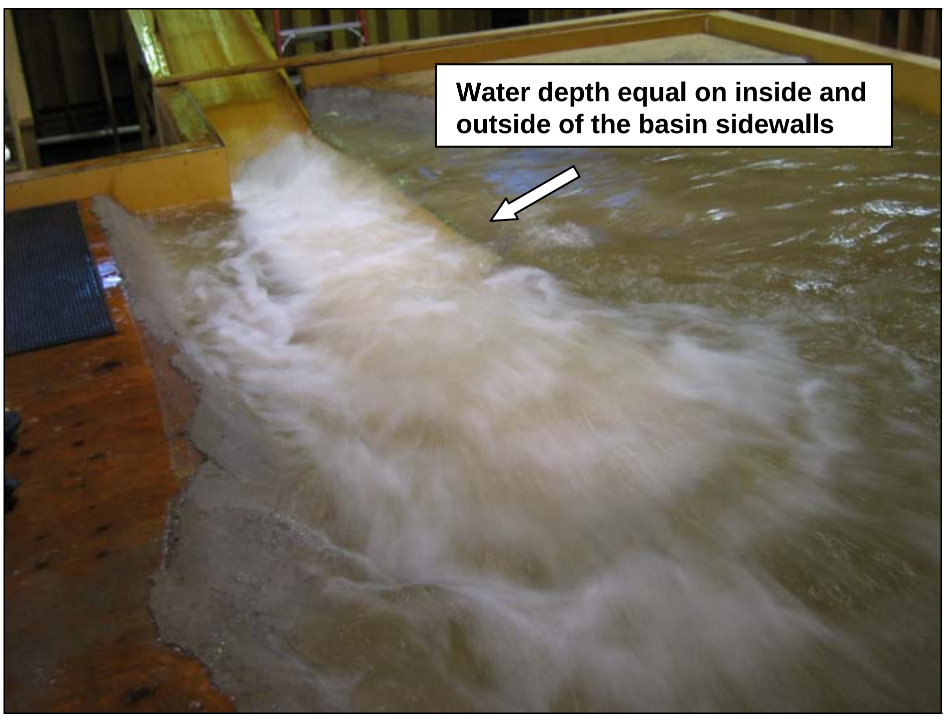

Figure 27 – Performance of the stilling basin with a tailwater equivalent to a 35,000 ft^3/s release. A combined release of 18,240 ft^3/s under reservoir elevation 3269.8 ft is shown.

Conclusions

With the current spillway configuration, discharges of 11,280 ft^3/s for spillway operation only and 14,400 ft^3/s for combined operation will occur at the top of dam elevation 3264 ft. If a 6-ft-high parapet wall is constructed at the top of dam to elevation 3270 ft, discharges of 14,965 ft^3/s for spillway operation and 18,240 ft^3/s for combined operation will occur at reservoir elevation 3269.8 ft.

With a parapet wall installed along the curved inlet structures and the roadway over the spillway inlet, the transition point from free flow to orifice flow occurs around 3269.8 ft, just below the top of the parapet wall at 3270 ft. Once the water catches on the roadway at 3269.8 ft, the water surface elevation raises by 4.5 ft which could cause overtopping of the parapet wall in the prototype. With wave action in the prototype, the transition may occur at a reservoir elevation lower than 3269.8 ft. From model observations, flow separates off the sharp corner on the left parking area, causing turbulence and a wave on the left side of the spillway. Adding a curve to the sharp corner may improve flow conditions and the capacity of the spillway.

The chute walls may overtop for discharges near the top of parapet elevation 3270 ft. Without any structural modifications to the spillway inlet, freeboard is less than 1 ft prototype from the break in wall slope (Sta. 9+70.00) to about 50 ft downstream of the slope change when one-third of the flow depth is added for bulking. At the break in floor slope at Sta. 9+22.32, the freeboard is 1.25 ft for spillway only operation and 1.6 ft for combined operation.

Model testing shows that the performance of the stilling basin is not acceptable above the design discharge of 8,120 ft^3/s with spillway only or combined flow. Since the hydraulic jump is swept out of the basin and the resulting boil spreads strongly in both the streamwise and transverse directions, significant damage to the stilling basin and downstream area may occur during high flow, low frequency events. Model results show that raising the tailwater elevation does not contain the hydraulic jump within the stilling basin. The increased tailwater suppresses the height of the turbulent boil, but not the length. The flow rate corresponding to the top of the parapet wall is over two times the design flow, so the stilling basin capability is exceeded regardless of tailwater.

Recommendations

When flows above the design discharge are passed through the existing spillway structure, there are several areas of hydraulic and structural concern that will need to be evaluated further. Based on the model results, the spillway chute walls may need to be raised between the break in floor slope and 50 ft downstream of the break in wall slope. During large releases, there is significant turbulence and flow surging in the stilling basin, leading to overtopping of the basin sidewalls and vibration of the splitter walls. The structural integrity of splitter walls and basin sidewalls should be evaluated under these high flow conditions.

The possibility of parapet wall overtopping when free flow converts to orifice flow at 3269.8 ft should be addressed. Although the water surface elevation increases quickly due to the small size of the model reservoir, waves in the prototype may trigger orifice flow prematurely. The duration of the flood and the amount of storage in the top 0.2 ft of the reservoir should be investigated to determine if the raise in water surface would be attenuated in the prototype. Investigations of potential wave heights should also be accomplished. Modifications to the proposed parapet wall geometry can improve flow conditions and may increase the spillway capacity. If a curve is not added and the findings from the additional investigations indicate a problem, it is recommended that the corrective action alternative be designed to pass the necessary discharge at a reservoir elevation of less than 3269.8 ft.

It is recommended that a risk assessment be conducted for the existing spillway structure operating under high flows. Although the stilling basin and streambed immediately downstream of the basin are founded on rock, there is some question as to whether the rock is competent enough to withstand the turbulence of the hydraulic jump during high discharges. If it is not, this could lead to head cutting under the stilling basin. An evaluation of the condition of the rock downstream from the stilling basin should be conducted with a risk assessment to determine if undermining of the stilling basin could cause dam failure.

Due to the hydraulic concerns relating to the spillway chute walls, stilling basin, and areas downstream of the basin, structural modifications may need to be made to satisfy risk criteria. If modifications to the existing structure are extensive, installation of a headwall across the existing spillway might be considered. The headwall would restrict flow into the spillway such that only non-damaging flows can pass through the existing structure. Headwall installation could eliminate the need for separate structural modifications to the chute walls and stilling basin. In this case, the corrective action alternative would need to be designed to accommodate the additional flow that is restricted from passing through the existing spillway structure.

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Appendix 1 – Model Observations

Table A1 – Model observations with spillway operation only.

Description	Measured Flow Rate (ft^3/s)	Measured Reservoir Elevation (ft)	Target Tailwater (ft)	Measured Tailwater (ft)	Reservoir Conditions
Channel capacity 3,000 ft^3/s	2,998	3246.8	3080.9	N/A	No overtopping.
Spillway design capacity 8,120 ft^3/s	8,160	3258.3	3086.4	3086.6	No overtopping. Smooth approach flow to inlet, but turbulence comes from water flowing over left approach channel topography.
Top of dam 3264 ft with 11,280 ft^3/s	11,348	3264.1	3088.5	3088.6	Water level at top of dam. Flow separates off the sharp corner of the parapet wall on the left parking area, producing a wave which bulks up the flow on the left side of the spillway. Adding a curve to the sharp corner would improve flow conditions and spillway capacity.
Top of parapet wall 3270 ft with 14,965 ft^3/s	14,927	3269.7	3090.7	3290.9	Water level near the top of parapet. Free flow just barely maintained in spillway. Bulked flow coming off of left curved inlet structure causes water to impact the roadway on the left side while smooth flow on the right side is able to maintain free flow.

Table A1 continued – Model observations with spillway operation only.

Description	Spillway Chute Condition	Outlet Works Condition	Outlet Works Chamber Condition	Stilling Basin Flow Conditions
Channel capacity 3,000 ft^3/s	Flow shallow in spillway chute. No splashing. No overtopping potential.	Closed	Spillway flow is not drawn into chamber.	Turbulence in first half of basin. No turbulent boil. No splashing. Flow even across basin width.
Spillway design capacity 8,120 ft^3/s	Flow contained within spillway chute. No splashing. No overtopping potential.	Closed	Spillway flow is not drawn into chamber.	Turbulent flow. Occasional splashing over basin sidewalls. Surging contained within basin walls. Flow even across basin width. Minimal splitter wall vibration.
Top of dam 3264 ft with 11,280 ft^3/s	Flow contained within spillway chute. No splashing. Overtopping potential appears minimal.	Closed	Spillway flow surges upstream about halfway into the transitional chamber.	Strong turbulence in basin. Some splashing over basin sidewalls, but not as much as with combined outlet works flows. Water shallow in upstream section of basin since hydraulic jump is swept downstream. Water depth nears the top of the sidewalls by the end of the basin. Flow even across basin width. Minimal splitter wall vibration.
Top of parapet wall 3270 ft with 14,965 ft^3/s	Flow contained within spillway chute. With bulking, chute walls may overtop, especially near break in floor slope and break in wall slope. No splashing.	Closed	Spillway flow surges upstream to transitional chamber overhang.	Strong turbulence in basin. Some splashing over basin sidewalls, but not as much as with combined outlet works flows. Water shallow in upstream section of basin because hydraulic jump is swept downstream. Water depth nears the top of the sidewalls by the end of the basin. Flow even across basin width. Strong reverse flow toward spillway face due to downstream boil. Tailwater at the top of the outside basin walls. Noticeable splitter wall vibration.

Table A1 continued – Model observations with spillway operation only.

Description	Hydraulic Jump Location and Strength	Exit Channel Flow Conditions
Channel capacity 3,000 ft^3/s	Jump in first half of basin. No boil.	Calm flow leaving basin. No turbulence or recirculation. Minimal wave action. Appears to be low erosion potential.
Spillway design capacity 8,120 ft^3/s	Jump occurs above endsill. Boil at end of basin walls is full width of basin, extending 24-32 ft prototype downstream of end of basin walls and boiling up 4-6 ft prototype above the normal water surface. Slight lateral spreading downstream of basin.	Calm flow leaving basin. Some turbulence continues downstream of basin, but boil contained within riprap section and does not spread strongly in lateral direction. Minimal wave action. Appears to be moderate erosion potential.
Top of dam 3264 ft with 11,280 ft^3/s	Jump occurs at the end of the basin walls. Jump is swept out of basin. Boil is the full width of basin, extending 40-48 ft prototype downstream of end of basin walls and boiling up 6-8 ft prototype above the normal water surface. Spreads strongly laterally and downstream of the endsill. Recirculating eddy behind left basin wall.	High velocity flow ends just downstream of the riprap section. Moderate wave action against right bank. Appears to be moderate/high potential for erosion.
Top of parapet wall 3270 ft with 14,965 ft^3/s	Jump occurs just downstream of end of basin walls. Jump is swept out of basin. Boil is the full basin width, extending 64 ft prototype downstream of end of basin walls and boiling up 8-10 ft prototype above the normal water surface. Spreads laterally and downstream of the endsill. Water splashes up over last 12 ft of the basin walls.	High velocity flow ends just downstream of the riprap section. Strong wave action against right bank. Appears to be high potential for erosion.

Table A2 – Model observations with combined spillway and outlet works operation.

Description	Measured Flow Rate (ft^3/s)	Measured Reservoir Elevation (ft)	Target Tailwater (ft)	Measured Tailwater (ft)	Reservoir Conditions
Outlet works capacity at crest elevation 3234.8 ft with 2,900 ft^3/s	2,902	3234.6	3080.8	N/A	No spillway flow.
Channel capacity 3,000 ft^3/s	2,998	3235.9	3080.9	N/A	Minimal flow over spillway.
Spillway design capacity 8,120 ft^3/s	8,126	3251.8	3086.4	3086.2	Smooth approach flow. No overtopping.
Top of dam 3264 ft with 14,400 ft^3/s	14,433	3263.8	3090.3	3090.5	Water level at top of dam. Flow separates off the sharp corner of the parapet wall on the left parking area, producing a wave which bulks up the flow on the left side of the spillway. Adding a curve to the sharp corner will improve flow conditions and capacity of the spillway.
Top of parapet wall 3270 ft with 18,240 ft^3/s	18,240	3269.7	3092.2	3092.4	Water level near the top of parapet. Free flow just barely maintained in spillway. Bulked flow coming off of left curved inlet structure causes water to impact the roadway on the left side while smooth flow on the right side is able to maintain free flow.

Table A2 continued – Model observations with combined spillway and outlet works operation.

Description	Spillway Chute Condition	Outlet Works Condition	Outlet Works Chamber Condition	Stilling Basin Flow Conditions
Outlet works capacity at crest elevation 3234.8 ft with 2,900 ft^3/s	No spillway flow.	Water depth is 5 ft in the conduit.	Flow through chamber is calm. Water surface is below splitter wall height.	Turbulent flow in center section only. Flow contained within basin. Water surface uniform.
Channel capacity 3,000 ft^3/s	Flow shallow in spillway chute. No splashing. No overtopping potential.	Water depth is 5 ft in the conduit.	Spillway flow is not drawn into chamber. Spillway flow does not seal outlet.	Turbulent flow in center section of basin. Water level higher in right & left sections than center. No splashing.
Spillway design capacity 8,120 ft^3/s	Flow shallow in spillway chute. No splashing. No overtopping potential.	Water depth is 5 ft in the conduit.	Spillway flow is not drawn into chamber. Outlet works flow is below splitter wall height.	Turbulent flow. Water level 10 ft prototype higher in right and left sections due to outlet works release. Water from the right and left sides overtop the splitter walls, entering the center portion of the basin. Occasional splashing over basin sidewalls. Minimal splitter wall vibration.
Top of dam 3264 ft with 14,400 ft^3/s	Flow contained within spillway chute. Overtopping potential appears minimal.	Water depth is 5 ft in the conduit.	Spillway flow is not drawn into chamber. Outlet works flow is near top of splitter wall.	Strong turbulence and splashing within basin, particularly in center section. Flow surges are 12-18 ft high and regularly surge out of the basin. Water surface uniform. Splitter walls experience noticeable vibration.
Top of parapet wall 3270 ft with 18,240 ft^3/s	Flow contained within spillway chute. With bulking, chute walls may overtop, especially near break in floor slope and break in wall slope.	Water depth is 5-5.5 ft in the conduit.	Spillway flow is not drawn into chamber. Outlet works flow is near top of splitter wall.	Strong turbulence and splashing within basin, particularly in center section. Flow surges are 18-24 ft high and regularly surge out of the basin. Strong reverse flow toward spillway face due to downstream boil. Tailwater is higher than the stilling basin walls, so water splashes into the basin. Splitter wall vibration significant.

Table A2 continued – Model observations with combined spillway and outlet works operation.

Description	Hydraulic Jump Location & Strength	Exit Channel Flow Conditions
Outlet works capacity at crest elevation 3234.8 ft with 2,900 ft^3/s	Jump occurs at end of splitter walls in center section. Turbulence contained within basin.	Calm flow leaving basin. No turbulence or recirculation. Minimal wave action. Appears to be low potential for erosion.
Channel capacity 3,000 ft^3/s	Small turbulent boil at end of center section. Turbulence contained within basin.	Calm flow leaving basin. No turbulence or recirculation. Minimal wave action. Appears to be low potential for erosion.
Spillway design capacity 8,120 ft^3/s	Jump occurs above endsill. Boil near the end of basin walls is the full width of the basin, extending 48 ft prototype downstream of basin walls and boiling up 4-6 ft prototype above the normal water surface. Some lateral spreading.	Calm flow leaving basin. Some turbulence continues downstream of riprap section. Moderate wave action against banks. Appears to be moderate/high potential for erosion.
Top of dam 3264 ft with 14,400 ft^3/s	Jump occurs above endsill. Boil is the full width of the basin, extending 72 ft prototype downstream of the basin and boiling up 6-8 ft prototype above the normal water surface. Spreads strongly in downstream and lateral directions. Strong wave action against banks. Recirculating eddy behind left basin wall.	High velocity flow ends just downstream of the riprap section. Moderate wave action against banks. Appears to be high potential for erosion.
Top of parapet wall 3270 ft with 18,240 ft^3/s	Jump occurs at end of basin walls and extends 84 ft prototype downstream of the basin. Boil width is greater than width of basin and spreads strongly in lateral direction. Boils up 10-12 ft prototype above the normal water surface. Recirculating eddy behind left basin wall. Strong wave action against banks.	High velocity flow ends just downstream of the riprap section. Strong wave action against banks. Appears to be high potential for erosion.

Table A3 – Model observations with spillway operation only. Increased tailwater represents the higher discharge anticipated from the addition of an auxiliary spillway structure.

Description	Measured Flow Rate (ft^3/s)	Measured Reservoir Elevation (ft)	Target Tailwater (ft)	Stilling Basin Flow Conditions	Hydraulic Jump Location & Strength
Spillway operation at top of parapet wall 3270 ft	14,927	3,270	Set to 3094.5 ft for 25,000 ft^3/s release	Water pours over the basin sidewalls causing continual splashing. Some reverse flow toward the spillway face due to downstream boil causes noticeable vibration of the splitter walls. The jump starts at about the same location as with the lower tailwater.	Jump is about 64-68 ft prototype downstream of the basin, but it is starting to drown out such that the boil raises only 6 ft prototype (rather than 8-10 ft). Recirculating eddy behind left basin wall is drowned out. Wave action against right bank is still very strong.
Spillway operation at top of parapet wall 3270 ft	14,927	3,270	Set to 3097.8 ft for 35,000 ft^3/s release	Water pours over the basin sidewalls in the first two-thirds of the basin causing continual splashing. In the downstream one-third of the basin, the water levels inside and outside the basin are the same. The splitter walls are completely submerged except for the location of jump initiation.	Jump lengthens to about 76-80 ft downstream of the basin, but it is drowned out such that the boil raises only 4 ft prototype above the surrounding water surface. All recirculation zones are drowned out. Waves splash up higher than the maximum topography in the model (elevation 3105 ft).

Table A4 – Model observations with combined spillway and outlet works operation. Increased tailwater represents the higher discharge anticipated from the addition of an auxiliary spillway structure.

Description	Measured Flow Rate (ft^3/s)	Measured Reservoir Elevation (ft)	Target Tailwater (ft)	Stilling Basin Flow Conditions	Hydraulic Jump Location & Strength
Combined operation at top of parapet wall 3270 ft	18,240	3269.7	Set to 3094.5 ft for 25,000 ft^3/s release	Water pours over the basin sidewalls causing continual splashing. Strong reverse flow toward spillway face due to the downstream boil causes violent vibration of the splitter walls. The jump starts at about the same location as with the lower tailwater.	Jump is still about 84-96 ft prototype downstream of the end of the basin, but boils up only 8 ft prototype (rather than 10-12 ft). Recirculating eddy behind left basin wall is drowned out. Wave action against right bank is still very strong.
Combined operation at top of parapet wall 3270 ft	18,240	3269.7	Set to 3097.8 ft for 35,000 ft^3/s release	Water pours over the basin sidewalls in the first two-thirds of the basin causing continual splashing. In the downstream one-third of the basin, the water levels inside and outside of the basin are the same. The splitter walls are completely submerged except for the location of the initiation of the jump.	Jump lengthens to about 96-112 ft prototype downstream of the basin, but it is drowned out such that the boil raises only 4-6 ft above the surrounding water surface (rather than 10-12 ft). All recirculation zones are drowned out. Waves splash up higher than the maximum topography in the model (elevation 3105 ft).