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Hydraulic Model Study of Fish Passage Features Below Cle Elum Dam

U.S. Department of the Interior
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Hydraulic Investigations and Laboratory Services Group
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14. ABSTRACT

This document describes the physical hydraulic model study of the upstream adult fish passage facility for Cle Elum Dam, Washington. The model study was focused on providing sufficient attraction flow to guide fish into the entrance of a fish ladder that will lead to a trap and haul facility. The model also was used to study flow conditions associated with the downstream juvenile fish passage outfall and modifications to the outlet works to maintain adequate energy dissipation with fisheries modifications in place.

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Hydraulic Model Study of Fish Passage Features Below Cle Elum Dam

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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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A fish recovery effort has been underway in the Yakima River basin since the 1980s. A significant objective of the effort has been to open up fish access to headwater areas upstream from 5 major storage dams in the basin: Bumping Lake, Tieton, Cle Elum, Kachess, and Keechelus. In 2003 the Bureau of Reclamation completed an appraisal-level assessment of alternatives for providing fish passage at the five dams and identified Cle Elum and Bumping Lake Dams as the highest priority sites for continued investigation of fish passage feasibility. A final planning report for Cle Elum Dam was completed in April 2011.

Proposed fish passage facilities for Cle Elum Dam include both downstream juvenile passage and upstream adult passage. This document describes only the physical hydraulic model study of the upstream adult fish passage facility and investigations of flow conditions associated with the downstream passage outfall, which would be located near the entrance to the adult passage facility. The downstream passage design is described in a separate report [1].

Model investigations led to several adjustments from the initial design to provide adequate flow conditions that promote safe and successful passage of migrating adults and juvenile fish. These adjustments included changes to the elevation and orientation of the juvenile conduit outfall, relocation of the adult fish ladder that leads to the trap and haul facility, and the addition of a splitter wall to isolate the adult ladder entrance and juvenile outfall from flow currents produced by outlet works flows.

Although the addition of the splitter wall produced better conditions for migrating fish, it compromised the energy dissipation characteristics of the stilling basin. Therefore, additional model investigations were conducted to resolve this issue. As a result, final recommended modifications include adding an insert section at the exit of the outlet works discharge conduit, to more closely center the outlet works jet within the new discharge channel formed by the splitter wall. In addition, two concrete blocks should be added to the existing stilling basin wall to help prevent tailwater sweep-out at the upstream end of the new channel.

Background

Cle Elum Dam, located on the Cle Elum River about 8 miles northwest of Cle Elum, Washington, was built in 1933 without fish passage facilities (Figure 1 and Figure 2). The dam expanded a natural lake that historically supported populations of three species of salmon (sockeye, coho and spring Chinook), steelhead, Pacific lamprey, bull trout and other resident fish. Lack of passage at the dam blocked access to the lake and upstream habitat for anadromous salmonids and contributed to the extirpation of sockeye salmon runs in the Yakima River basin. The absence of passage has also isolated local populations of bull trout and may have prevented their recolonization of head waters [2].

A fish recovery effort has been underway in the Yakima River basin since the 1980s. The Bureau of Reclamation (Reclamation) began studying fish passage at the five major storage dams in the Yakima basin (Bumping Lake, Tieton, Cle Elum, Kachess, and Keechelus) as a result of commitments made to Washington State and the Yakama Nation related to Safety of Dams (SOD) modifications at Keechelus Dam.   In 2003 Reclamation completed an appraisal-level assessment of alternatives for providing fish passage at the five dams and identified Cle Elum and Bumping Lake Dams as the highest priority sites for continued investigation of fish passage feasibility [3].

Figure 1. — Cle Elum dam and spillway, with the interim flume and outlet works operating.

A final planning report for fish passage improvements at Cle Elum Dam was completed in April 2011 [2].   The project will provide fish passage to historic habitat and restore biodiversity to enhance the natural production of salmon and lamprey in the upper Cle Elum subbasin.

This collaborative project involves the Bureau of Reclamation, Washington State Department of Ecology (Ecology), Washington State Department of Fish and Wildlife (WDFW), and the Yakama Nation. This project has two components, 1) fish passage facilities design, with Reclamation taking the lead, and 2) a fish reintroduction program developed by the Yakama Nation with assistance from WDFW. Fish expected to benefit include sockeye, coho and spring Chinook salmon, and Pacific lamprey. The project also benefits the Upper Middle Columbia River steelhead and bull trout, two species listed as threatened under the Endangered Species Act. This report only addresses the physical model studies associated with the design of the fish passage facilities.

Introduction

Proposed fish passage facilities for Cle Elum Dam include both downstream juvenile passage and upstream adult passage. This document only describes the physical hydraulic model study of the upstream adult fish passage facility and investigations of flow conditions associated with the downstream passage outfall which is near the adult ladder entrance. The downstream fish passage design is described in a separate report [1]. A trap and haul facility is proposed in lieu of a long fish ladder that would need to accommodate typical reservoir fluctuations in excess of 100 vertical feet. Trap and haul methods for upstream fish passage have been used successfully at other large dams in the Pacific Northwest. Fish would swim up a short ladder into the collection facility. When adequate numbers of fish are collected in the facility, they would be placed into a fish transport truck to haul fish upstream for release in the reservoir and upstream tributaries. The adult collection facility would be operated from early March to late December. Ladder flow and auxiliary flow for attraction would be supplied by pumps that will draw water from the stilling basin through four cylindrical screens located on the south basin wall. During adult fish passage, there will be times of overlapping operations of the adult ladder, the downstream passage outfall, and the outlet works, which all share the same stilling basin.

Purpose

The purpose of the hydraulic model study was to determine how to use the proposed auxiliary flow system to provide sufficient attraction flow to guide fish into the ladder entrance. In addition to outlet works flows, there may be an overlap between the upstream and downstream passage seasons. Therefore, the study included investigations of the downstream passage outfall, the outlet works outfall, the ladder outfall, the auxiliary flow system screened intake and discharge sites, and the flow patterns in the stilling basin between the various intakes and outfalls. There is also the potential for the temporary downstream passage flume (interim flume) on the spillway to remain operational after the construction of the new facilities; therefore the effect of the interim flume flow on ladder attraction flow was also investigated.

Throughout the design process, Reclamation collaborated with a Technical Yakima Basin Storage Fish Passage Work Group (CORE team) of biologists, engineers, and other specialists from Federal , State, Tribal, and local entities to evaluate flow conditions for their effectiveness and potential for injury to fish.

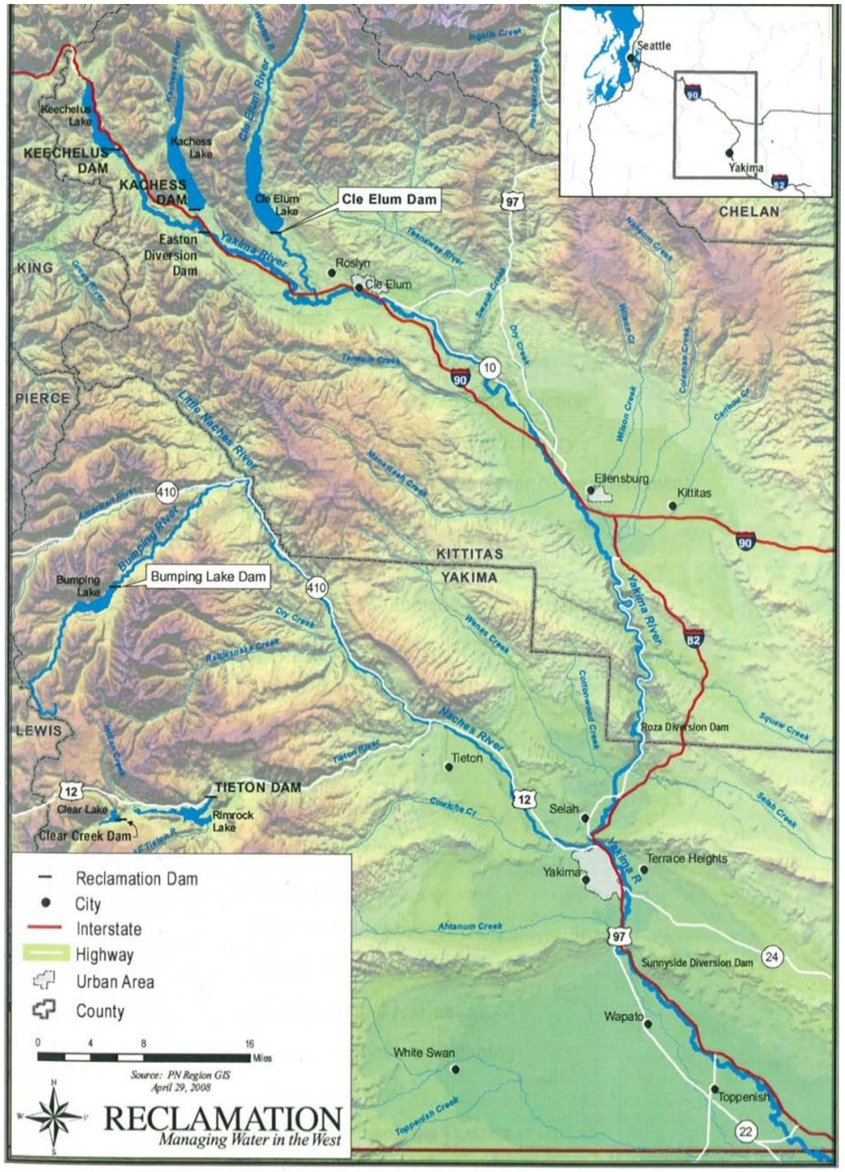


Figure 2. — Location map for Cle Elum Dam.

The Physical Model

A physical model study was conducted by Reclamation's Hydraulic Investigations and Laboratory Services Group in Denver, Colorado. The physical model included the downstream end of the spillway chute, beginning upstream from the outlet works conduit exit (near station 13+32.5 ft), the stilling basin area, and topography that extends about 200 ft beyond the end of the spillway stilling basin. The extents of the model are shown in Figure 3. Due to laboratory space constraints, the model was constructed as a mirror image of the existing spillway (Figure 4). Features included in the initial configuration of the model were:

- The fish ladder entrance located 19 ft downstream from the outfall conduit.
- A truncated portion of the downstream passage outfall conduit and conduit exit with outfall invert elevation at 2113.8 ft.
- Four cylindrical screens extending inside the stilling basin.
- The outlet works conduit beginning at sta. 23+53.
- The interim downstream fish passage flume along the surface of the spillway beginning at sta. 13+25.5.
- River channel bathymetry extending about 200 ft downstream from the end of the stilling basin.

A 1:10 geometric scale was used to construct the model. Similitude between the model and the prototype is achieved when the ratio of the major forces controlling the physical processes are the same. Since gravitational and inertial forces dominate open channel flow, Froude scale similitude was used to establish a kinematic relationship between the model and the prototype. The Froude number, which represents the ratio of inertial to gravitational forces, is expressed as

$$F_r = \frac{v}{\sqrt{gd}}$$

where v = velocity, g = gravitational acceleration, and d = flow depth. When equal Froude numbers are maintained between the model and the prototype, specific scaling relationships exist between model and prototype values of key flow parameters. In the equations that follow, the r subscript refers to the ratio of the prototype and model values:

Length ratio: $L_r = L_m/L_p = 10$

Velocity ratio: $V_r = L_r^{1/2} = (10)^{1/2} = 3.16$

Discharge ratio: $Q_r = L_r^{5/2} = (10)^{5/2} = 316.23$

Flow to the outlet works conduit was provided from a pipe extending from the laboratory pipe chase. Flow into the downstream passage conduit and interim fish passage flume were provided from pipes extending from the opposite end of the pipe chase and controlled by separate laboratory pumps. In addition, to evaluate fish attraction flow conditions, water was drawn from the stilling basin through the cylindrical screens and pumped into the auxiliary chamber and fish ladder. However, neither the auxiliary flow chamber nor the fish ladder was modeled with adequate detail to investigate internal flow conditions. Ladder flow was set to 6 ft^3/s for all test cases. Combined ladder and auxiliary flow for attraction was initially set to 186 ft^3/s based on four cylindrical screens providing 45 ft^3/s each. This value was later changed to 121 ft^3/s and then 145 ft^3/s during the course of the study due to changing screen and pump designs. HEC-RAS was used to generate a tailwater curve that provided tailrace water surface elevation as a function of total flow coming into the stilling basin. This data compared well with the Reclamation gage data for the Cle Elum stilling basin (Table 1). In addition, HEC-RAS was used to generate flow depths and velocities for the interim juvenile passage flume and for the downstream passage conduit at stations where flow entered into the model from each of these truncated components (Table 2).

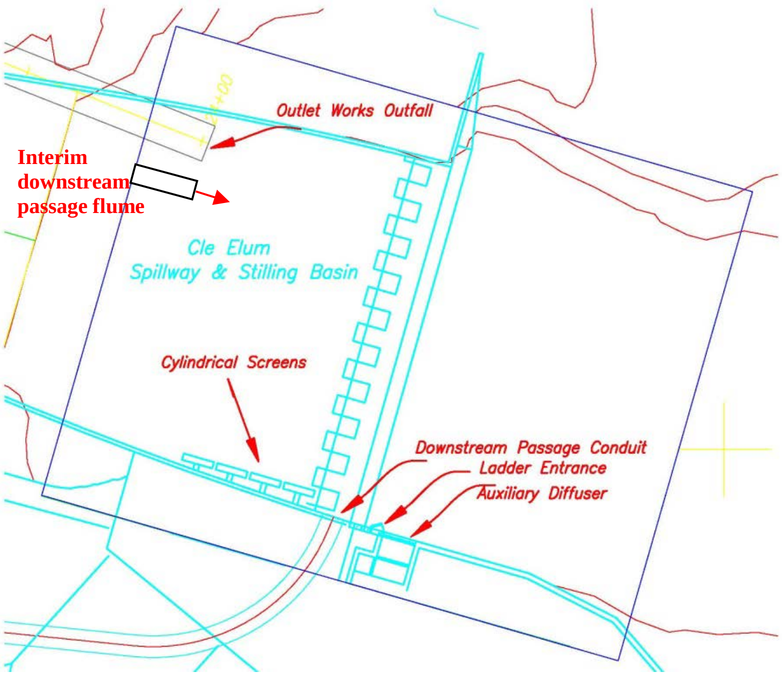


Figure 3. — Dark blue line indicates extents of the physical model.

Figure 4. — Physical model constructed as a mirror image on a 1:10 geometric scale.

Model Study Test Plan

Model investigations were used to evaluate the influence of the interacting flow combinations on attraction flows for the ladder entrance as well as potential injury for juveniles exiting at the outfall. Photographs, videos, velocity measurements, and general observations of flow conditions were used to help evaluate the various flow combinations and to determine necessary modifications to the structure.

The initial flow combinations tested (case numbers 1-7, Table 3), provided by the CORE team, represent expected flow conditions, including:

- Upstream passage of adults in a separate season,
- Upstream and downstream passage during a combined season, and
- The above flow combinations in conjunction with outlet works flows.

Additional flow combinations (Case numbers 8-19, Table 3) were added to cover the full range of possible combinations expected in the prototype and to determine the magnitude of discharge where upstream currents are strong enough to begin carrying the outfall or auxiliary/ladder (ladder) flows upstream into the stilling basin. The flow combinations tested for all model configurations generally included but were not limited to those shown in Table 3.A tail gate installed at the downstream end of the physical model was used to set tail race elevation based on Reclamation gage data obtained at Cle Elum Dam (Table 1). All values and dimensions given in the tables and throughout this document are stated in terms of the prototype.

Modifications to improve juvenile fish passage and the effectiveness of adult attraction flows included:

- Changing the elevation, orientation, and alignment of the downstream fish passage outfall conduit,
- Modifying the angle or alignment of the fish ladder entrance, and
- Adding a splitter wall to isolate flow currents produced by outlet works flows.

Table 1. — Tailwater surface elevation and outlet works exit velocity as a function of discharge.

Total Discharge into Stilling Basin (ft^3/s)	Gage Water Surface Elevation (ft)	HEC-RAS Exit Velocity for outlet works for Discharge in Column 1 (ft/s)
100	2108.5	6.8
200	2108.9	8.2
250	2109.1	8.8
400	2109.3	18.4
600	2109.7	24.4
1000	2110.5	32.3
1500	2111.1	37.1
2000	2111.7	40.4
2500	2112.2	42.6
3000	2112.7	44.6
3200	2112.9	45.3
3500	2113.2	46.6

Table 2. — Exit velocities for the juvenile conduit and interim flume as a function of discharge. (based on cut and fill methods for conduit installation).

Discharge (ft^3/s)	Juvenile Conduit Exit Velocity (ft/s)	Interim Flume Exit Velocity (ft/s)
100	N/A	38.5
200	41	44.2
300	43	47.3
200	46	49.4

Table 3. — Flow rate combinations tested for most configurations.

Prototype Case Number	Total Discharge (ft^3/s)	Outlet Works (ft^3/s)	Juvenile Outfall Conduit (ft^3/s)	Downstream Interim Flume (ft^3/s)	Combined Auxiliary and Ladder Flow (ft^3/s)
1	220	220	0	0	186
2	220	100	125	0	186
3	500	300	200	0	186
4	220	100	0	120	186
5	500	100	300	100	186
6	3400	3100	300	100	186
7	3500	3200	300	0	186
8	3600	3200	400	0	186/121
9	3400	3200	200	0	186/121
10	2400	2000	400	0	186/121
11	2300	2000	300	0	186/121
12	2200	2000	200	0	186/121
13	1900	1500	400	0	186/121
14	1800	1500	300	0	186/121
15	1400	1000	400	0	186/121
16	1300	1000	300	0	186/121
17	900	500	400	0	186/121
18	800	500	300	0	186/121
19	400	100	300	0	186/121

Fish Passage Investigations

Phase I – Initial Model Configuration

Initial investigations were conducted over a range of flow combinations expected to occur in the prototype including those listed in Table 3. Juvenile outflow velocities were set based on HEC-RAS modeling that assumed a conduit slope consistent with a cut-and-fill approach for construction of the downstream fish passage conduit. This was used as a worst case scenario since geological testing had not yet been conducted to determine if a tunneling approach could be used. The velocities tested for each flow rate are listed in Table 2.

Initial testing demonstrated that as outlet works flows were increased, a large eddy formed in the basin that caused flow to be directed upstream along the opposite wall of the basin (the wall furthest from the outlet works). These investigations showed that at high outlet works flows, both the juvenile outfall and ladder flows were carried upstream into the stilling basin (Figure 5). In fact, flows from any source with a magnitude of 400 ft^3/s or greater caused the ladder flow to be carried upstream into the basin. This flow pattern could make it difficult for adult salmon migrating upstream to find the ladder entrance since they are unlikely to sense the source of the flow as they approach the basin. In addition, the upstream currents may cause juvenile salmon exiting at the outfall conduit to be pushed into the stilling basin where they could become disoriented regarding the direction of the river channel and therefore may be more susceptible to predation.

Another concern with this configuration was that the height of outfall above the tailwater elevation produced a deep plunging jet that may cause injury to juvenile fish (Figure 6). The outfall velocities (greater than 40 ft/s) are significantly higher than the maximum outfall impact velocity of 25 ft/s stated in NMFS standard criteria [4], therefore a skimming type flow for the juvenile outfall was recommended by CORE team members.

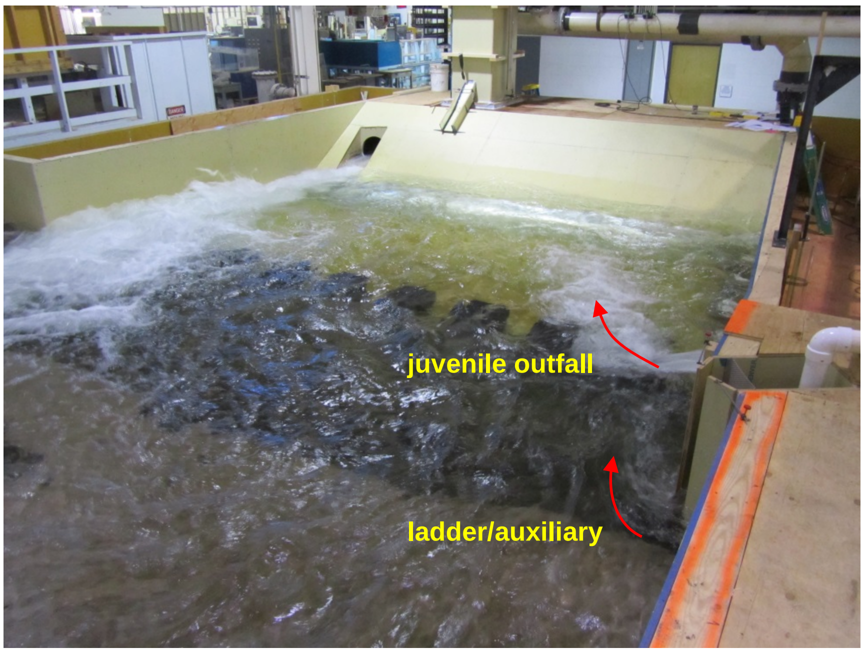


Figure 5. — Model operating with discharges for the outlet works, juvenile outfall, and ladder/auxiliary flows at 3200 ft^3/s, 300 ft^3/s, and 186 ft^3/s respectively. The juvenile conduit invert is positioned at elevation 2113.8 ft.

As a result of these initial investigations, the outfall elevation was lowered by 3.5 ft (to approximately Elev. 2110.3) to provide flow conditions closer to a skimming flow condition throughout the full range of tailwater elevations expected during outfall operations. In addition, a splitter wall, the same height as the stilling basin sidewall, was installed in the stilling basin, to mitigate upstream flow currents being produced on the opposite side of the basin. The splitter wall created a 54 ft wide channel extending from the spillway face to the downstream end of the stilling basin (Figure 7) to isolate the outlet works flow from the rest of the stilling basin.

During this initial series of tests it was also determined that the effect of operating the interim flume in combination with other flows coming into the basin was insignificant. Therefore to simplify testing, all subsequent tests were conducted without the interim flume operating.

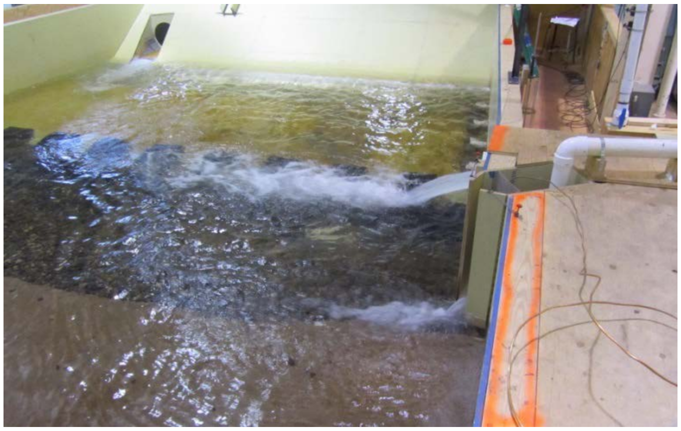


Figure 6. — Model operating with discharges for the outlet works, juvenile outfall and ladder/auxiliary flows at 300 ft^3/s, 300 ft^3/s and 186 ft^3/s respectively. The juvenile conduit invert is positioned at elevation 2113.8 ft.

Figure 7. — Model operating with splitter wall in place with discharges for the outlet works, juvenile outfall and ladder/auxiliary flows at 400 ft^3/s, 300 ft^3/s and 186 ft^3/s respectively. The juvenile conduit invert is positioned at elevation 2110.2 ft.

Phase II – Splitter Wall, Outfall Conduit at Elevation 2108.4

For this series of tests, with the splitter wall in place, the juvenile conduit was lowered an additional 2 ft to elevation 2108.4 and the angle of the conduit was changed to 60 degrees (referenced from the stilling basin centerline) to project outfall flows more toward the river channel (Figure 8). Some tests in this series were conducted with "best-guess" tunnel velocities of 33 ft/s, 30 ft/s and 28 ft/s for outfall discharges of 400 ft^3/s , 300 ft^3/s , and 200 ft^3/s respectively, since preliminary information indicated that tunneling through the right abutment of the spillway may be a viable option for the juvenile conduit.

In these tests the ladder flow was not carried upstream into the stilling basin until outlet works discharge was increased above 800 ft^3/s. Flow from the juvenile outfall projected well across the width of the stilling basin for outlet works flows up to 1500 ft^3/s (Figure 9). Although ladder flows were carried upstream at outlet works flows greater than 800 ft^3/s, ladder flow merged with the juvenile outfall jet and was carried across the width of the basin (Figure 9). This indicated that allowing ladder flows to merge with the outfall flow may provide additional attraction for adults trying to find the ladder entrance. As a result of these investigations, final recommendations include relocating the adult ladder entrance close to the juvenile outfall and providing flows through the juvenile outfall conduit throughout the adult migration season, whenever possible, even if juveniles are no longer migrating downstream.

Further testing, with the realigned outfall conduit positioned at elevation 2108.4, showed that as outlet works flows were increased, outfall flow became partially submerged and then experienced some rollover as outlet works flows exceeded 1500 ft^3/s (Figure 10). Since there was some concern of injury to juveniles due to rollover, the next step was to reposition the outfall elevation to 2109.25 ft, a level between the previous two elevations tested.

Figure 8. — The juvenile conduit is angled at 60 degrees with invert elevation 2108.4 ft. Model operating with discharges for the outlet works, juvenile outfall and ladder/auxiliary flows at 100 ft^3/s, 400 ft^3/s (v=33 ft/s) and 186 ft^3/s respectively.

Figure 9. — Model operating with discharges for the outlet works, juvenile outfall and ladder/auxiliary flows at 1500 ft^3/s, 400 ft^3/s (v = 33 ft/s)and 186 ft^3/s respectively. The juvenile conduit is angled at 60 degrees with invert elevation 2108.4 ft.

Figure 10. — The juvenile conduit is angled at 60 degrees with invert elevation 2108.4 ft. Model operating with discharges for the outlet works, juvenile outfall and ladder/auxiliary flows at 3200 ft^3/s, 400 ft^3/s (v=33 ft/s) and 186 ft^3/s respectively.

Phase III – Splitter Wall, Outfall Conduit at Final Elevation, New Ladder Position, Excavated Channel, New Outfall Velocity Data

For this series of tests the ladder entrance was moved upstream, closer to the juvenile outfall, as shown in Figure 11 (10 feet from the outfall conduit centerline to the nearest ladder entrance centerline). Although the photo shows two entrances to the ladder, only one entrance was included in final design, so all testing was conducted with only a single ladder entrance operating. In addition, to allow for a deeper channel along the trajectory of the juvenile outfall, topography was excavated at a 10:1 slope beginning near the end of the outfall conduit and extending along the projection of the conduit centerline until the top of the existing 4:1 slope was reached (Figure 11).

Just prior to this series of tests, new geologic data became available indicating tunneling would be used for the juvenile conduit construction. Newly calculated velocity data, based on the milder slope used for the juvenile conduit, are given in Table 4. These velocity values were used for subsequent evaluations of juvenile outfall flows. In addition new design requirements for the auxiliary flow pumps and screens limited the maximum flow for the auxiliary to 115 ft^3/s, so testing was conducted with a total combined ladder and auxiliary flow of 121 ft^3/s.

Figure 11. — Ladder relocated closer to outfall conduit with newly excavated topography. The juvenile conduit is angled at 60 degrees with invert elevation 2109.25 ft.

Investigations with this configuration showed that although rollover was no longer an issue at the outfall exit (invert elevation 2109.25), the outfall jet was still turned upstream due to strong upstream currents when the outlet works was operated above 1500 ft^3/s (Figure 12).

Table 4. — Calculated exit tunnel velocities for juvenile outfall.

Discharge	Exit Velocity Juvenile Conduit
200	19
300	21
400	23

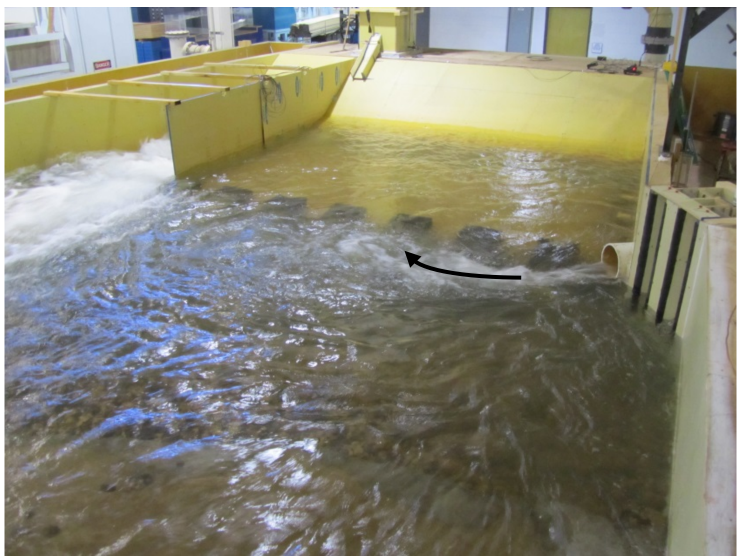


Figure 12. — The juvenile conduit is angled at 60 degrees with invert elevation 2109.25 ft. Model operating with discharges for the outlet works, juvenile outfall and ladder/auxiliary flows at 2000 ft^3/s, 300 ft^3/s (v=21 ft/s), and 121 ft^3/s respectively.

Phase IV – Extended Splitter Wall, Outfall Conduit at Final Elevation

In an attempt to further mitigate the upstream flow currents near the outfall at high outlet works discharges, the splitter wall was extended an additional 56 feet in length to the top of the upward sloping topography (where it meets the river channel) downstream from the stilling basin (Figure 13). Investigations conducted with this configuration proved to be successful in providing a well-projected downstream flow for the juvenile outfall for all outlet work operations tested up to 3200 ft^3/s. Therefore, this was the final recommended design (Figure 13 and Figure 14).

Figure 13. — Splitter wall is extended an additional 56 feet downstream from the end of the stilling basin. Outlet works operating with outlet works discharge at 3200 ft^3/s.

(a) (b)

Figure 14. — Model operating with discharges for the outlet works at (a) 2500 ft^3/s and (b) 3200 ft^3/s. Juvenile outfall and ladder/auxiliary flows operating at 300 ft^3/s (v= 21 ft/s) and 121 ft^3/s, respectively. The juvenile conduit is angled at 60 degrees with invert elevation 2109.25 ft.

Summary of Fish Passage Enhancements

With the extended splitter wall in place, outfall flows were projected diagonally downstream and across the width of the river channel for all levels of operations of the outlet works up to the maximum flow tested, 3200 ft^3/s. Ladder flows at higher outlet works discharges were carried upstream to immediately merge with the outfall flow, as expected.

Model investigations determined that the following modifications to the original design will provide safe flow conditions for migrating adults and juvenile fish:

- The adult ladder entrance should be moved close to the juvenile outfall so that outfall flows can provide additional attraction for migrating adults.(Exact location to be determined by designers)
- The juvenile outfall channel should be angled downstream, 60 degrees away from the stilling basin side wall, to project the outfall flow toward the river channel.
- The location of the juvenile conduit invert at 2109.25 provided best performance over the full range of outlet works operations tested. However since tunneling was approved for the construction of the conduit, outfall velocities dropped below 25 ft/s (NMFS maximum velocity criteria) [4]. Therefore a skimming type flow for the juvenile conduit outfall is no longer necessary, and the elevation of the conduit can be adjusted at designer's discretion.
- To isolate adult fish ladder and juvenile fishway outfall flows from the effects of outlet works flows, a splitter wall should be added, extending from the spillway face to a location 56 feet beyond the downstream end of the stilling basin.

The addition of the extended splitter wall, the relocated ladder, and the relocated and realigned juvenile conduit have been accepted by CORE team members and will therefore become a part of the final design. However, with the splitter wall in place the energy dissipation performance of the outlet works was compromised. Therefore, this issue was addressed with additional model testing.

Outlet Works Modifications

With final modifications in place to provide good attraction flows for migrating adults while providing safe downstream passage for juvenile salmon, a new problem was identified. With the new splitter wall in place, energy dissipation in the outlet works stilling basin was compromised, especially at high outlet works flow releases. The original design of the dam had the outlet works pipe approaching the stilling basin through the face of the spillway at an angle (Figure 15) so that the outlet works jet would project across the basin to better utilize the width of the basin for energy dissipation when the outlet works operates alone. The large size of the stilling basin allowed it to provide energy dissipation for both outlet works and spillway flows. However, with the splitter wall in place, the angled jet emerging from the outlet works impinges on the splitter wall and at the same time sweeps all tailwater out of the channel in the area near the splitter wall at the upstream end of the new channel (Figure 16 and Figure 17). This causes excessive turbulence, flow recirculation, and spray when flow enters the narrow channel at high discharges and could lead to significant erosion or abrasion damage within the concrete basin.

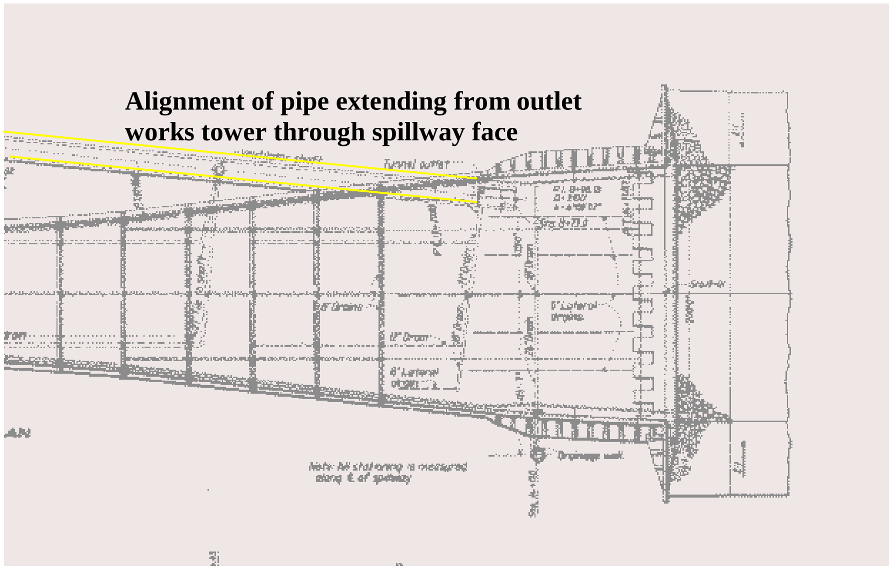


Figure 15. — Cle Elum spillway drawing showing outlet works pipe alignment.

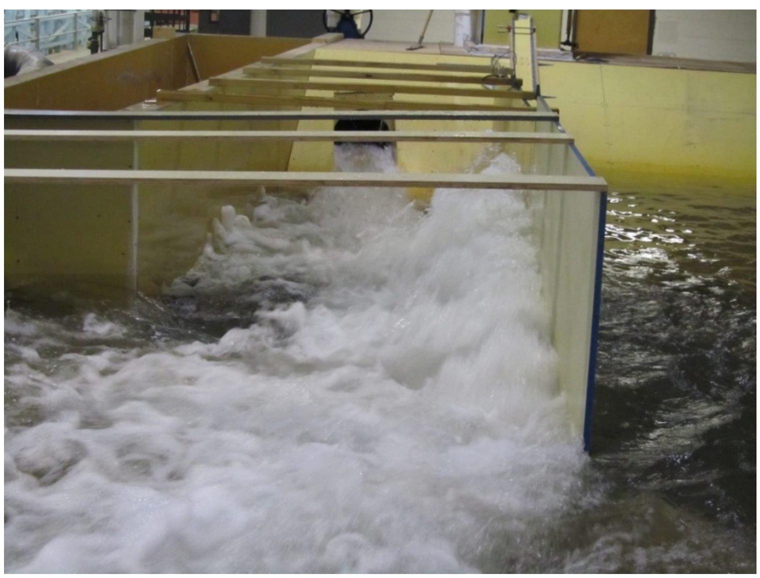


Figure 16. — Cle Elum dam outlet works operating at 3200 ft^3/s with new splitter wall in place.

Figure 17. — Cle Elum dam outlet works operating at 3200 ft^3/s. High velocity angled jet sweeps tailwater downstream away from splitter wall.

To mitigate this problem three separate approaches were investigated.

- Adding open slots cut into the splitter wall to supply tailwater near the upstream end of the new outlet works channel.
- Adding a quarter-pipe extension to the outlet works pipe to recenter the outlet works discharges within the new channel and prevent sweepout.
- Adding a concrete insert, flush with the spillway face to recenter the outlet works discharges and prevent sweepout.

New outfall velocities were calculated for this series of tests since the juvenile conduit was realigned by designers for final design (Table 5).

Table 5. — Final calculated exit tunnel velocities based on final design for juvenile outfall conduit.

Discharge	Exit Velocity Juvenile Conduit
200	14.4
300	15.5
400	17.0

Splitter Wall Slots

This set of investigations used a range of open slots cut out of the splitter wall to provide tailwater to the upstream end of the new channel, thus pushing the jet more toward the center of the channel and providing better energy dissipation. Before the slots were added, the splitter wall was expanded in thickness, moved inward, and reduced in height to account for prototype loading and to provide sufficient room for fish exiting the interim flume from the spillway. This narrowed the outlet works channel to 50.5 ft with a new wall height of 19 ft (top elevation 2116 ft). In addition, the juvenile passage conduit was moved to elevation 2110.9 for final design. Tests began by opening slots nearest the upstream end of the stilling basin to minimize effects on the outfall flow and to minimize splashing that may attract migrating adults. The first test was conducted with four fully open slots, with the first open slot located near the upstream end of the stilling basin, 97 feet upstream from the upstream face of the dentated end sill (Figure 18). Each slot was two feet wide with four feet of spacing between slots, beginning one foot above the invert surface (sloped spillway face or basin floor).

Figure 18. — View looking toward outlet works through 6 fully open slots in the splitter wall.

This configuration improved energy dissipation in the new channel, but not significantly. Several more tests were conducted with increasing open slot area with each test. With 7 fully open slots cut out of the splitter wall, energy dissipation performance was very good (Figure 19). The added tailwater was enough to push the outlet works jet away from the splitter wall and more toward the center of the channel (Figure 20). Energy dissipation with this configuration in place was very good throughout the full range of discharges tested. However, the addition of the slots also produced upstream currents in the stilling basin that once again affected the direction of the outfall flow. With the outlet works discharging below 2000 ft^3/s, the juvenile outfall flow was redirected across the width of the basin toward the splitter wall. With the outlet works discharging at 2000 ft^3/s and above, the outfall jet was turned upstream. Therefore the effectiveness of the splitter wall was compromised (Figure 21). The upstream currents in the basin could once again make it difficult for migrating adults to find the ladder entrance as well as jeopardize the ability of juvenile salmon to find the downstream river channel. As a result of these findings, a slotted wall was not considered to be a viable solution for improving outlet works energy dissipation.

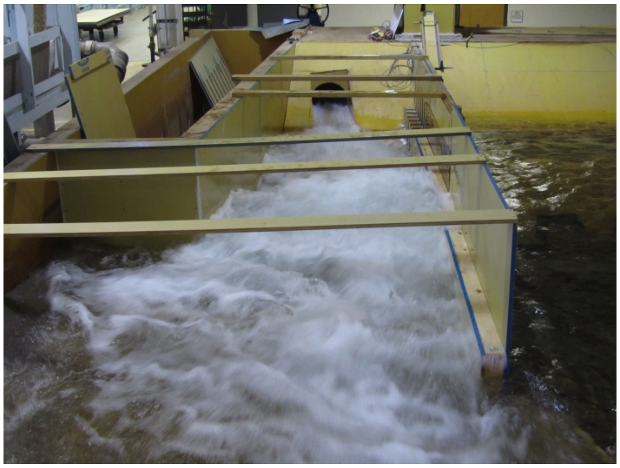


Figure 19. — Cle Elum dam outlet works operating at 3200 ft^3/s with 7 fully open slots provides good energy dissipation.

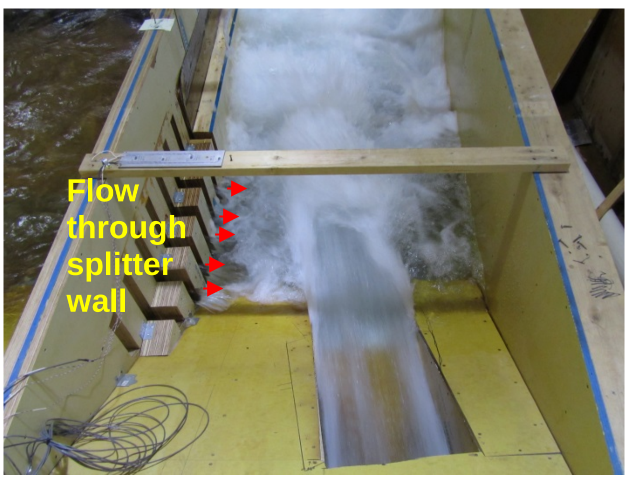


Figure 20. — Cle Elum Dam outlet works operating at 3200 ft^3/s with 7 fully open slots that allow tailwater to fill in the void and recenter the outlet works jet.

Figure 21. — Flow conditions at the adult ladder and juvenile fish passage outfalls during tests of the slotted splitter wall with seven fully open slots. Juvenile conduit is angled at 60 degrees with invert elevation 2110.9 ft and flush with stilling basin side wall. Discharges for the outlet works and juvenile outfall are 3200 ft^3/s and 300 ft^3/s (v= 21 ft/s), respectively.

Quarter-Pipe Extension

A section of sheet metal was used to provide a quarter pipe extension at the end to the outlet works pipe. The extension matched flush with the end of the outlet works pipe at the upstream end and gradually tapered inward toward the pipe centerline to redirect flow toward the center of the new splitter wall channel. Five separate pipe extension modifications, with decreasing radii, were tested and the design that provided best performance tapered from a 7 foot radius at the upstream end to a 5 ft radius at the downstream end (Figure 22). The pipe extension works well, recentering and lifting the flow as it emerges from the pipe and projecting it beyond the toe of the spillway (Figure 23 and Figure 24) so that tailwater level is maintained on both sides of the jet as it enters the tailrace. The bottom of the jet tends to skim off the water surface in the tailrace causing some turbulence along the water surface when the outlet works is operated at 3200 ft^3/s, but overall performance is good with this design. However, one drawback of the pipe extension design is that it extends above the face of the spillway by about 4.5 ft in order to contain the deeper flow that results from the narrowed section of the extended quarter-pipe (Figure 23). Concern over having any extension protruding beyond the spillway face led to further investigations.

Figure 22. — A quarter-pipe extension is attached at the downstream end of the outlet works pipe to redirect the exiting jet more toward the center of the new channel.

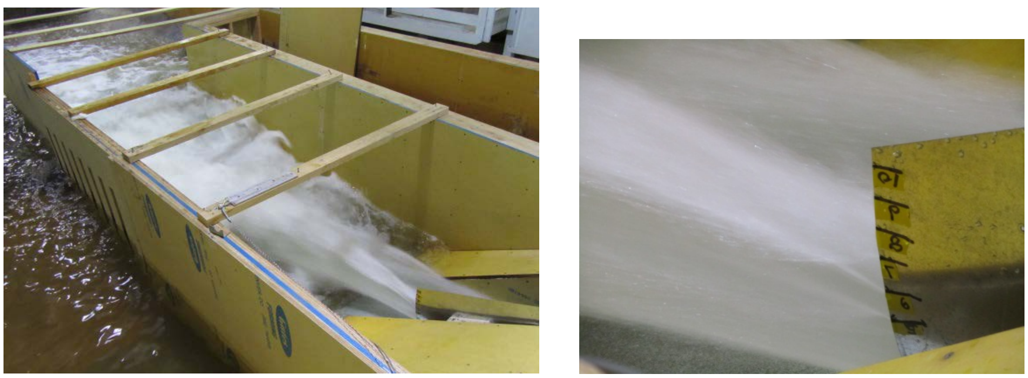


Figure 23. — Cle Elum dam outlet works operating at 3200 ft^3/s. Quarter pipe must extend about 4.5 ft (prototype) above the spillway surface to contain the deeper jet.

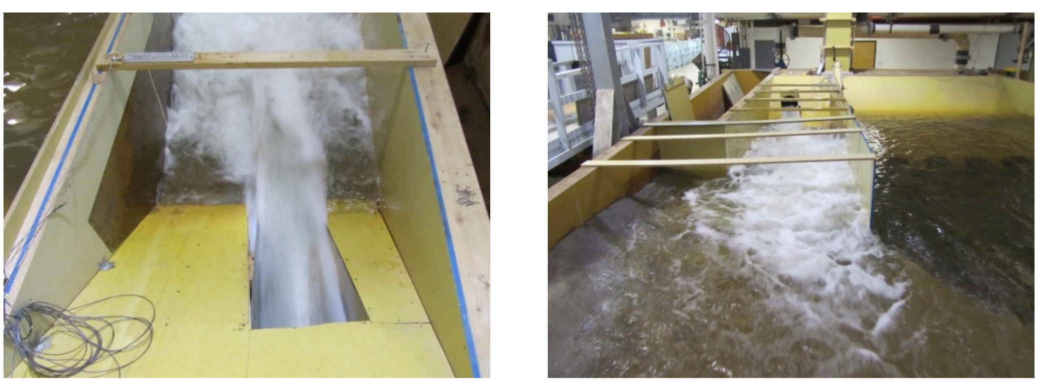


Figure 24. — Cle Elum dam outlet works operating at 3200 ft^3/s. The quarter-pipe extension recenters and lifts the exiting jet to prevent tailwater from being swept out.

Outlet Works Recessed Insert

The next series of tests were conducted with inserts that remained flush with the spillway face, to redirect flow toward the center of the splitter wall channel. Each insert was recessed inside the concrete inset at the end of the outlet works pipe (the area cut out from the spillway face to accommodate the outlet works) (Figure 25). The initial design for the insert began from the top corner of the existing inset and then extended flush with the spillway surface at a constant angle until the new surface merged with the existing spillway surface. The insert for the initial design extended 3 ft inside the existing concrete cut-out at the lower end. For each consecutive test the angle of the insert was increased so that the lower end point was moved in 1 ft increments until best performance was achieved. In each case the inside wall of the insert dropped vertically from the top of the new angled surface and then merged into a radius that tapered into the invert floor. The radius is warped from the end of the pipe downstream to where the new surface merges with the existing spillway surface (Figure 25).

Best performance occurred when the downstream end of the insert merged with the spillway face at a distance of 7 feet inside from its original location. Although the exit channel narrows from a 14 ft diameter pipe to a 7 foot width at the downstream end, flow depth and velocity at the outlet works exit does not change significantly since the jet rolls up the side of the new insert before leaving the spillway face. However, although tailwater sweepout near the upstream end of the splitter wall channel was significantly improved, further improvement was needed to achieve the desired level of energy dissipation (Figure 26). With the new insert in place to more closely center the emerging jet within the new splitter wall channel, three approaches were investigated to improve tailwater sweepout at the upstream end.

1) Adding submerged rectangular cutouts in the splitter wall near the upstream end of the channel to supply tailwater.
2) Increasing the height of the end sill blocks to increase tailwater depth within the channel.
3) Adding jetty-like blocks attached to the inside of both walls of the new channel to create a backwater effect to increase tailwater at the upstream end of the channel.

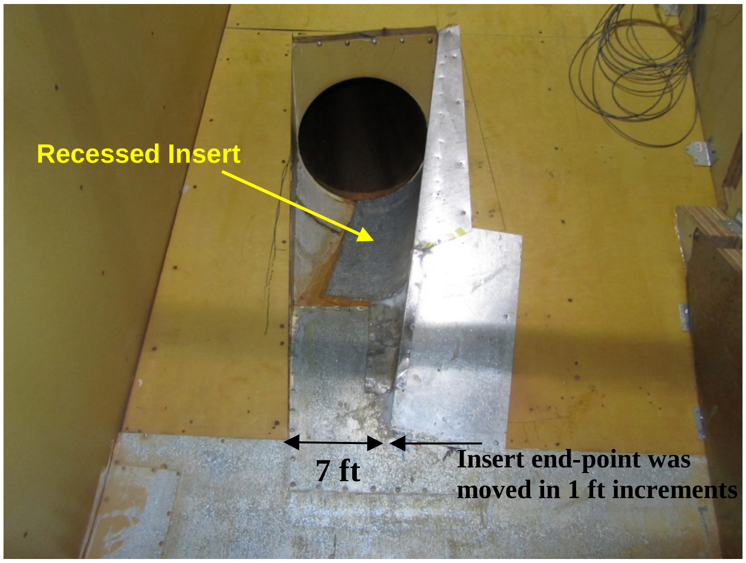


Figure 25. — Recessed insert installed to redirect outlet works discharges

Figure 26. — With 7 ft insert some sweepout on the right side still occurs.

Splitter Wall Cutouts

Rectangular cutouts were added to the splitter wall. Unlike the full-height slots tested earlier, each opening was located near the stilling basin floor beginning 1.0 ft above the invert surface of the stilling basin, in hopes that the submerged openings would not significantly affect the trajectory of the juvenile outfall flow. The following configurations were tested for this series of investigations :

1. Two 2.0 ft by 2.0 ft openings
2. Two, three and four 2.0-ft wide by 3.5-ft high openings
3. Three 2.0-ft wide by 3.0-ft high openings

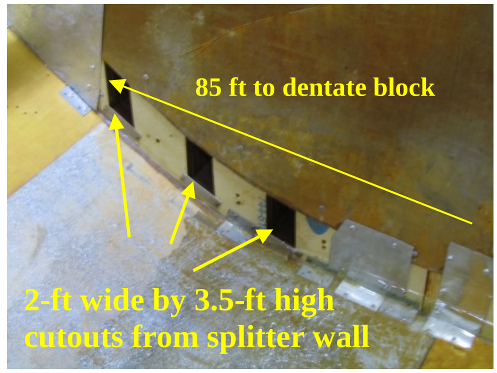


Figure 27. — Recessed insert in conjunction with three openings cut into splitter wall.

In each case tested the first opening was located a distance of 85 ft upstream from the upstream face of the dentate blocks. Best overall performance for this series of investigations occurred with three 2.0-ft wide by 3.5-ft high openings (Figure 27). With this configuration in place stilling basin dissipation was very good and the juvenile outfall jet, unaffected by flow through the cut-outs, continued to project well downstream as desired (Figure 28). However, some sweepout on the right side of the jet was still present (Figure 29). Testing with reduced open area did not provide adequate energy dissipation, and when total open area was increased, the trajectory of the outfall was affected.

In addition, although the three 2-ft wide by 3.5-ft high submerged openings are unlikely to attract migrating adults there was some concern that fish could congregate in the vicinity of the splitter wall, and if they passed through, would likely not survive at high outlet works discharges. As a result, a new series of investigations was performed to prevent tailwater sweepout without adding openings to the splitter wall.

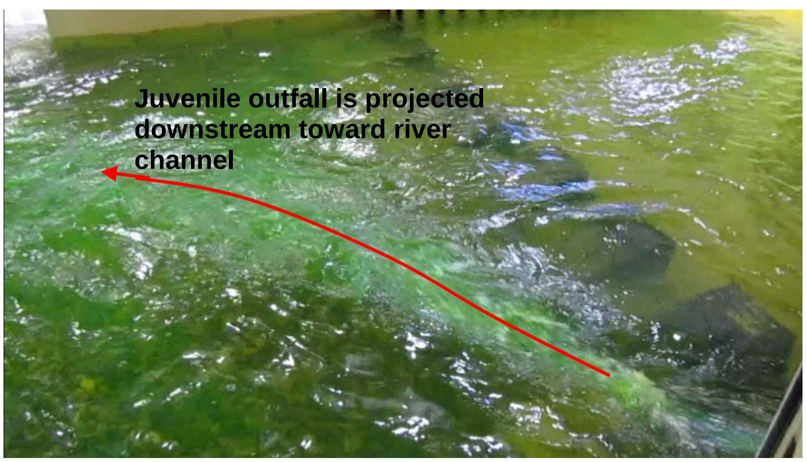


Figure 28. — Juvenile outfall flow projects downstream. Outlet modifications include recessed insert and three 2- ft wide by 3.5 high rectangular openings.

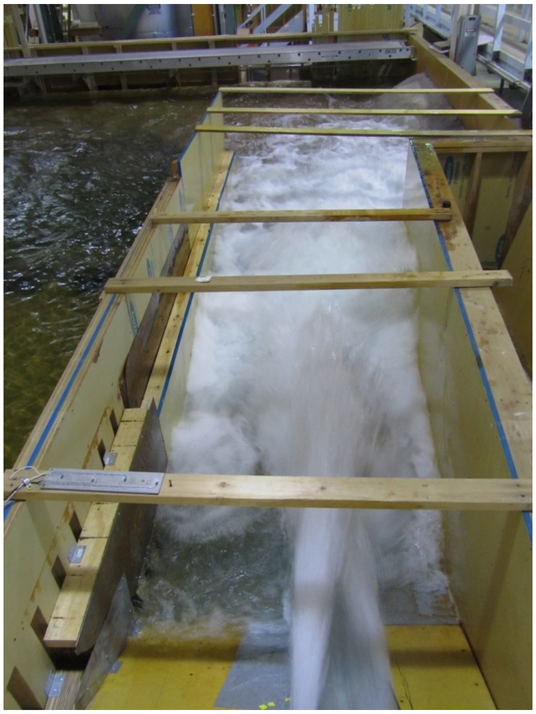
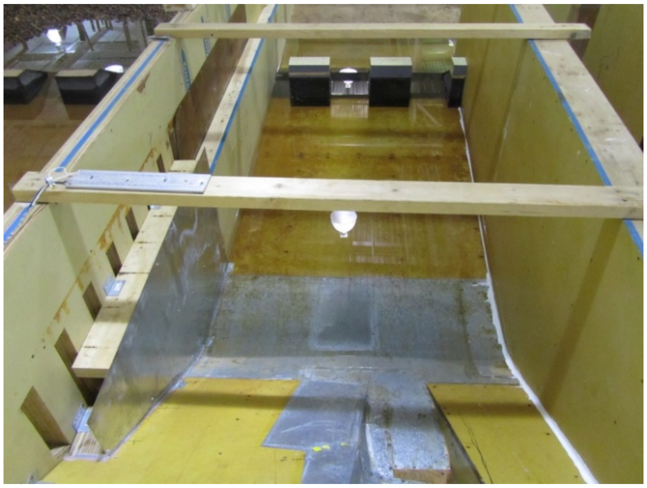


Figure 29. — Cutouts in splitter wall provide tailwater to left side of splitter wall channel.

Raised End Sill Blocks

The end sill blocks located at the end of the stilling basin within the splitter wall channel were increased in height by 3.125 feet for these investigations (Figure 30). The increased height of the blocks had no effect in preventing sweepout at the upstream end of the channel and in addition, a high rolling boil was created near the end of the basin where flow impacted the higher blocks (Figure 31). Therefore, performance for this configuration was considered unacceptable.



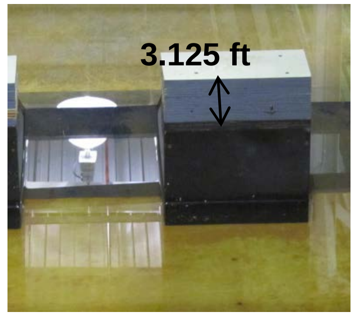


Figure 30. — Height of end sill blocks increased by 3.125 ft to 13.125 ft.

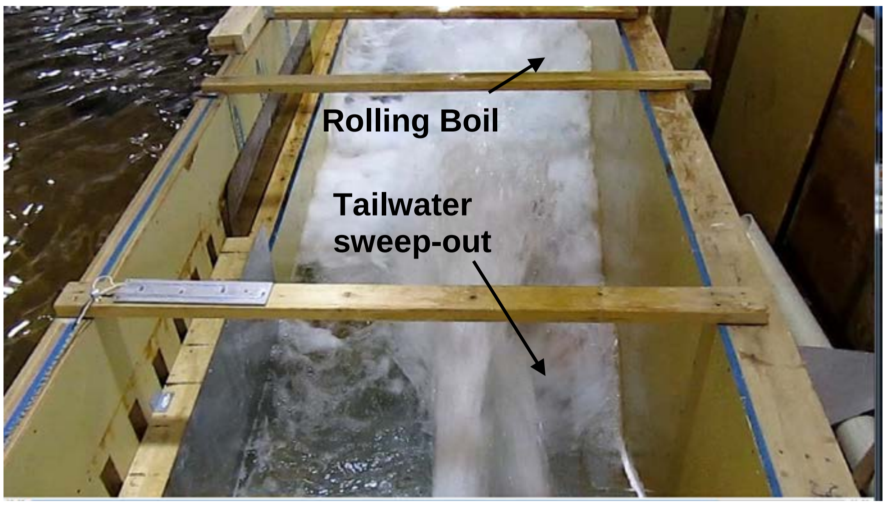


Figure 31. — Outlet works operating at 3200 ft^3/s with higher end sill blocks.

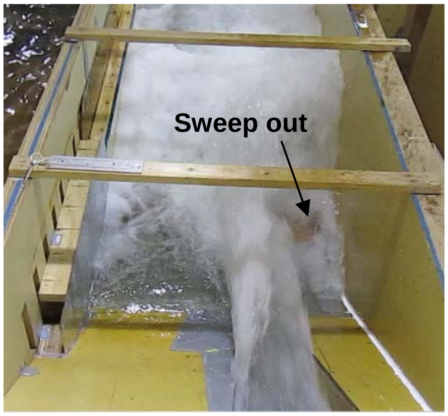
Jetty Blocks

Two blocks—one attached to each side wall of the new outlet works channel—were tested for this series of investigations in an attempt to use a backwater effect to produce tailwater at the upstream end of the channel. Tests for these investigations were conducted up to the maximum discharge of 4000 ft^3/s since there will be times when the outlet works will be operated up to that level. For simplification, initial block design consisted of blocks only 2.5 feet thick with vertical faces on the upstream and downstream sides. Block height was varied from 19 ft (same height as the splitter wall) down to 13 ft and block widths of 4 ft, 4.25 ft and 4.5 ft were tested. The location of the blocks was varied from 20 ft to 55 ft upstream from the end sill blocks (measured from upstream face to upstream face). This series of tests showed that a block width of 4.5 feet was necessary to provide adequate performance. Several block configurations investigated did a reasonably good job of providing tailwater to the upstream end of the channel. However, because the trajectory of the jet changes with discharge it was difficult to find a location for the blocks that was effective in preventing sweep-out on the right side of the channel throughout the full range of discharges tested (Figure 32a and Figure 32b).

As a result, a second block was added, attached to the outside wall of the channel (the existing stilling basin side wall) at a separate location to try to maintain backwater throughout the full range of discharges. This time, block height started at 13 feet with a block width of 4.5 feet. At the same time, the shape of each block was changed to include geometry required for structural support based on block height. For this series of tests, block locations and heights were adjusted for each subsequent test based on performance observed from the previous test.

The final block configuration consisted of two blocks attached to the outside wall of the new channel and one block attached to the splitter wall (Figure 33). This arrangement provided good performance throughout the full range of discharges tested. The two blocks positioned on the outside wall were 5 feet high by 4.5 feet wide and 3 feet high by 4.5 feet wide, located 40 feet and 55 feet, respectively, upstream from the dentated end sill (upstream face to upstream face) (Figure 34a). The splitter wall block was 5 feet high by 4.5 feet wide, and was located 35 feet upstream from the upstream face of the dentated end sill (Figure 34b). With this configuration in place, tailwater at the upstream end of the channel remained adequate throughout the full range of discharges tested up to a maximum of 4000 ft^3/s providing good energy dissipation and rarely splashing above the height of either wall (Figure 35). In addition, the outfall flow continued to project well downstream toward the river channel for all outlet works discharges (Figure 36).

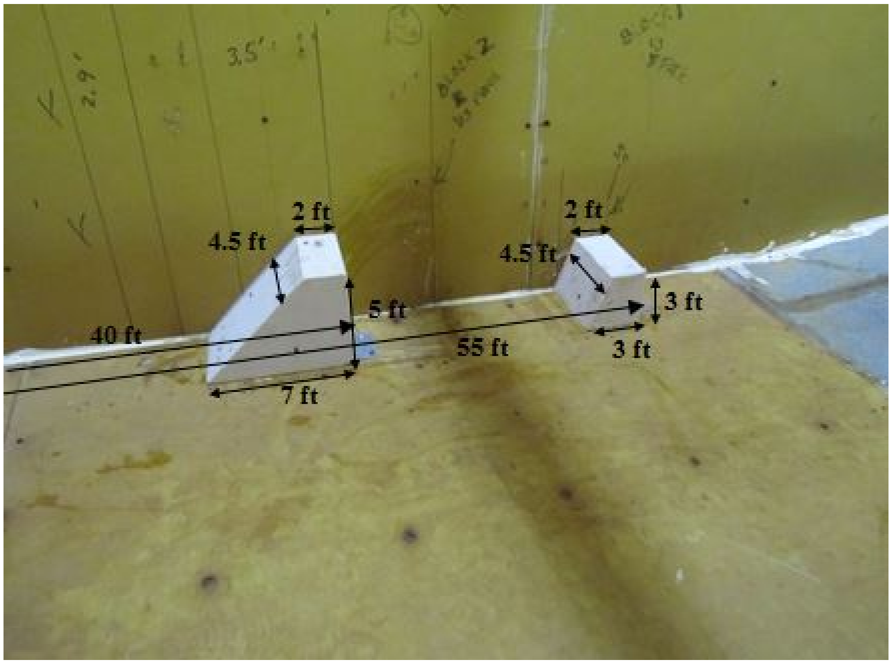
a)



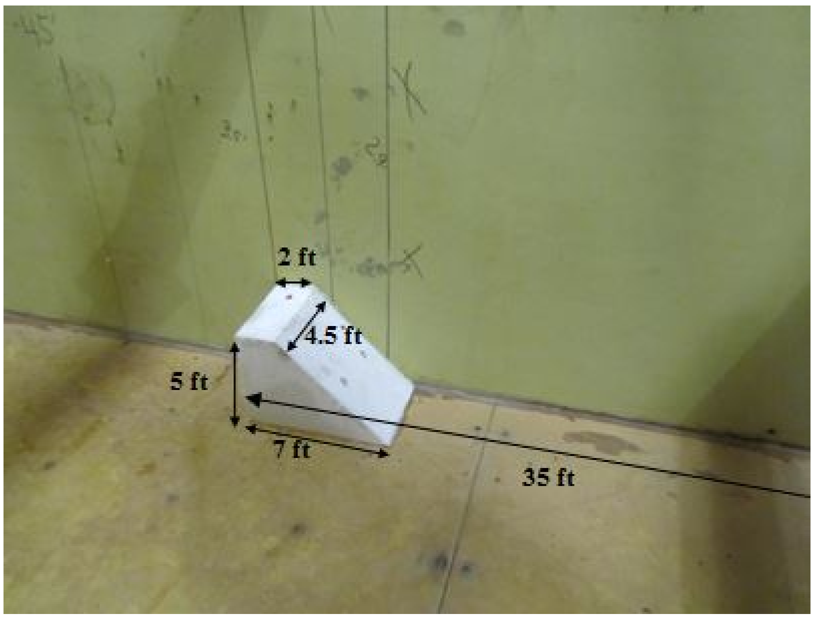
b)

Figure 32. — Initial jetty block configuration with one block attached to each wall of outlet works channel. Blocks positioned 35 ft upstream from end sill are a) effective at lower flows up to 2500 ft^3/s and b) inadequate at higher flows (4000 ft^3/s shown).

Figure 33 — Final outlet works modifications show optimal geometry and positioning of blocks, in conjunction with 7 ft recessed outlet works insert.



a)



b)

Figure 34. — Final geometry for basin blocks added to a) outside wall and b) splitter wall, to prevent tailwater sweep-out.

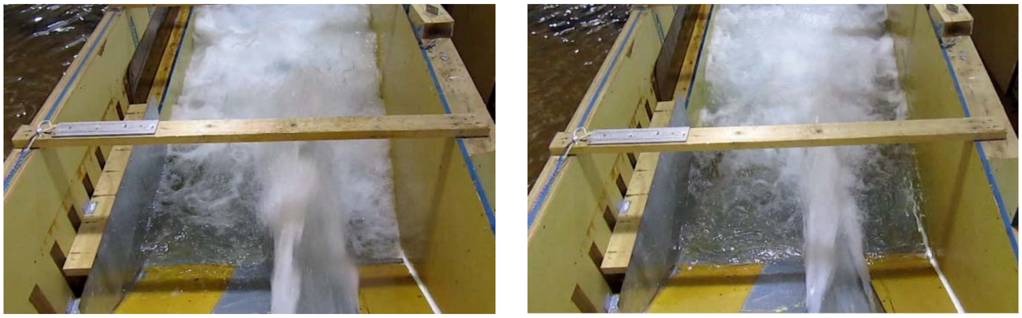


Figure 35. — Stilling basin shown operating at a) 4000 ft^3/s and b) 1500 ft^3/s with final modifications in place.

Figure 36. — Outfall flow projects well downstream throughout all discharges from the outlet works with final modifications in place. Outlet works and juvenile outfall operating at 4000 ft^3/s and 300 ft^3/s respectively.

Conclusions

Model investigations determined that the following modifications to the initial design will improve performance of the outlet works stilling basin as well as provide safe flow conditions for migrating adults and juvenile fish:

- The adult ladder entrance should be moved close to the juvenile outfall so that outfall flows can provide additional attraction for migrating adults.(Exact location to be determined by designers)
- The juvenile outfall channel should be angled at 60 degrees (referenced to the stilling basin side wall) to project the outfall flow toward the river channel.
- A splitter wall extending from the spillway face to a location 56 feet beyond the downstream end of the stilling basin should be added to mitigate flow currents that carry juvenile outfall flows upstream into the stilling basin.

- A recessed insert (Figure 25 and Figure 33), flush with the spillway face, should be added at the end of the outlet works pipe to provide a more centered outlet works jet projecting into the new channel formed by the splitter wall
- Three blocks should be added to the new stilling basin channel side walls. The final block configuration and geometries are shown in figures 33 and 34 and consist of two blocks attached to the outside wall and one block attached to the splitter wall of the new channel to prevent tail water sweep-out throughout the full range of outlet works discharges expected in the prototype.

It is worth noting that due to the excessively narrow channel formed by the splitter wall, tailwater sweep-out was extremely sensitive to the geometry and location of the jetty blocks. Due to this sensitivity and to ensure adequate stilling basin performance was maintained, additional tests and modifications to the final design were conducted after structural support for the blocks was added.

With the above modifications in place, safe conditions should be provided for migrating adult and juvenile fish. In addition outlet works energy dissipation will be provided at a level comparable to the original design, prior to fisheries modifications.

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