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Managing Water in the West

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Inskip Diversion Dam Physical Hydraulic Model Studies

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A 1:5 and a 1:8 scale physical hydraulic model of features of the Inskip Diversion Dam on South Fork Battle Creek in northern California were constructed at Reclamation's Hydraulic Laboratory in Denver, Colorado to investigate a pre-construction design of a new facility that incorporates a sediment settling chamber, a fish screen, auxiliary water supply, fish ladder and a multi-gated fish ladder entrance chamber. Modifications to the fish ladder entrance chamber, fish ladder exit chamber, sediment settling basin, and auxiliary flow entrance were recommended based on model results. Rating curves and operational guidance were developed for the different structures in the system and include the fish screen baffle percent open area, fish ladder entrance chamber gates, auxiliary water supply system, sediment sluice gate, swing gate, and tilt gate.

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Inskip Diversion Dam Physical Hydraulic Model Studies

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Introduction

Project Background

The Inskip Diversion Dam is one of 15 dams located along Battle Creek in Tehama County, California as shown in Figure 1. It was constructed in 1930 and is owned and operated by Pacific Gas and Electric (PG&E). The current facilities include a 28-foot-high masonry diversion dam, an intake structure and canal to supply water to an off-site hydropower facility, and an Alaska Steeppass fish ladder. As part of the Battle Creek Salmon and Steelhead Restoration Project, Inskip Diversion Dam will be modified to include a fish screen and a 28-pool fish ladder with a multi-gated entrance chamber. Prior to construction, PG&E and all stakeholders of the Battle Creek Salmon and Steelhead Restoration Project requested the Bureau of Reclamation's (Reclamation) Hydraulic Investigations and Laboratory Services group to create a physical model of the modifications.

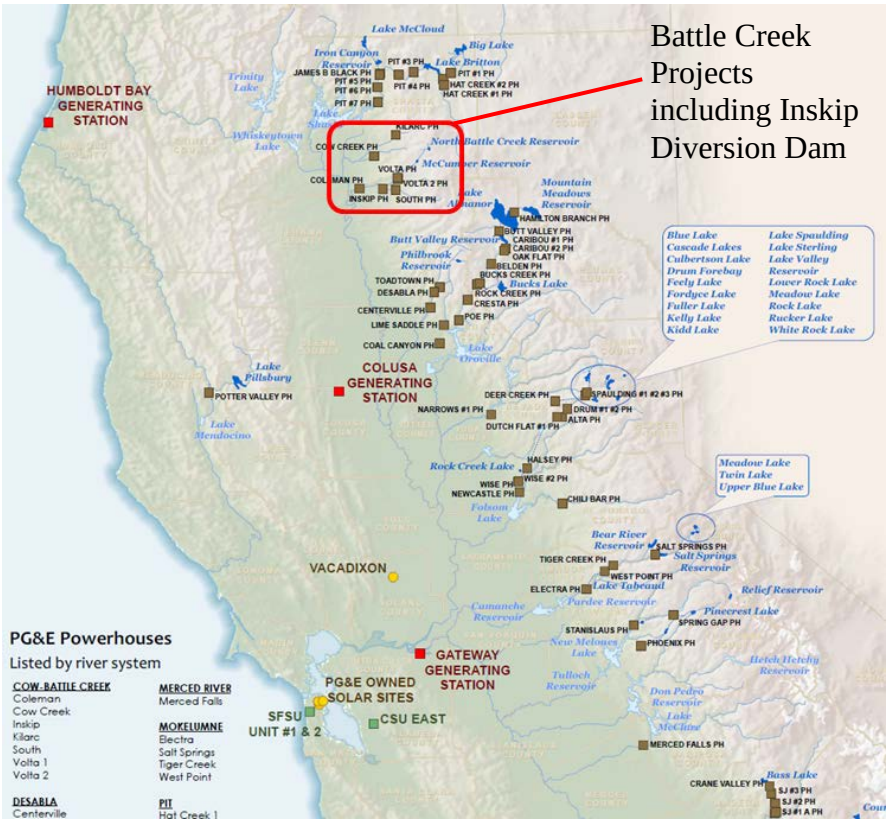


Figure 1. Location map of Inskip Diversion Dam in northern California

Inskip Diversion Dam Operation Requirements

The Inskip Diversion Dam is operated according to two primary documents created by the Battle Creek Salmon and Steelhead Restoration Project; the Memorandum of Understanding (MOU, 1999) and the Preliminary Engineering Concepts Technical Report (2000). The MOU was created between the Reclamation, National Marine Fisheries Service, U.S. Fish and Wildlife Service, California Department

of Fish and Game and PG&E. These documents outline the minimum instream flows and the maximum diversion that is allowed at the Inskip facility. The documents contain the following specifications:

- The diversion dam can provide up to 220 cfs of screened water to the Inskip Canal. It will typically be diverting less than 112 cfs.
- The design flow of 1700 cfs was calculated based on a 72 hour average daily flow that has a 1 in 10 recurrence interval. (Note: an updated hydrological analysis has recalculated this flow to be 1870 cfs).
- Ten percent or more of the design flow should be discharged from the fish ladder entrance chamber (combination of Auxiliary Water Supply (AWS) and fish ladder flows).
- Design flow for the fish ladder is 39 cfs.
- Approach velocity along the fish screen face = 0.33 ft/s
- Sweeping velocity must limit screen exposure for fish to no more than 60 seconds. For Inskip diversion with a screen length of 125 feet, this requires a sweeping velocity greater than 2.08 ft/s.
- Maximum vertical velocity from the AWS floor diffuser in the fish ladder entrance chamber is 1.0 ft/s
- Minimum instream flows for South Fork Battle Creek are:
    - 40 cfs (May through November)
    - 86 cfs December through March)
    - 61 cfs (April)

Model Objectives

- Verify that the fish screen approach velocities do not exceed design criteria of 0.33 ft/s based on National Marine Fisheries Service criteria for fish screens (NMFS, 2011)
- Qualitatively evaluate the effectiveness of the sediment basin upstream of the fish screen in capturing sediment coming from the intake
- Qualitatively evaluate the effectiveness of the sediment basin sluice gate at clearing sediment retained in the sediment basin
- Create a rating curve for the swing gate at the downstream end of the fish screen
- Evaluate the diversion canal tilt gate operations downstream of the fish screen
- Investigate the operation of the multi-gated fish ladder entrance chamber with respect to the ability of the design to clear sediment from the river side of the gate
- Assess entrance chamber gate openings required to ensure a fishway entrance hydraulic drop of 1.0 to 1.5 feet between the water surface inside the entrance chamber and the river.
- Investigate how sediment passing from the existing sluice gate incorporated in the current diversion dam interacts with the design of the fish ladder entrance chamber and in-channel excavation.
- Create stage-discharge rating curves for the diversion dam, river and fish ladder entrance chamber.
- Modify the physical model as needed to improve the hydraulic performance of the facility.
- Develop operational recommendations from the physical model study

Model Description

In order to satisfy the model objectives, it was determine that two physical models that utilize different scaling ratios would be required. The differing model scales allowed better resolution for tasks such as velocity confirmations along the fish screen and space constraints within the laboratory. Since hydraulic properties are consistent between fish ladder pools not impacted by entrance or tailwater effect, fish ladder pools #3-21 were not modeled. Both models were constructed in Reclamation's hydraulics laboratory in Denver, Colorado in 2015 and 2016.

The first model was built at a 1:5 (model : prototype) geometric scale and included the diversion canal, headworks gate, intermediate gate, sediment basin and sluice, fish screen, swing gate, fish ladder exit chamber, pools 1 through 3 of the Half Ice Harbor style fish ladder, AWS intake, and diversion canal tilt gates. The features included in the 1:5 scale model are shown in Figure 2, while the model extent is outlined in red.

The second model was built at a 1:8 geometric scale and included the diversion dam, the diversion dam sluice gate, pool 21 through 27 of the Half Ice Harbor style fish ladder, the fish ladder entrance chamber, the excavated entrance pool on the river side of the fish ladder entrance chamber, and the river topography between the dam and approximately 300 feet downstream of the fish ladder entrance chamber as it was prior to the construction activities in 2017 that modified the topography. Due to the construction, overbank flow patterns in the physical model may differ from what would be observed in the river channel following construction activities. The features of the 1:8 scale model can be found below in Figure 3.

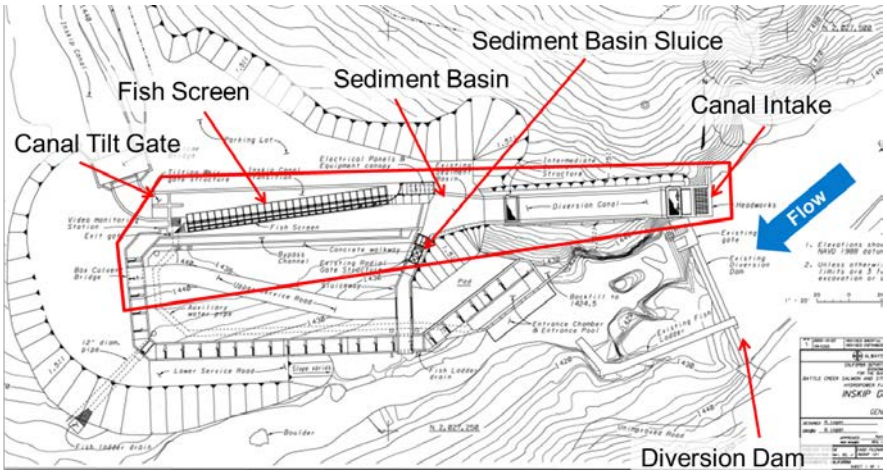


Figure 2. 1:5 scale physical model of the fish screen and ladder.

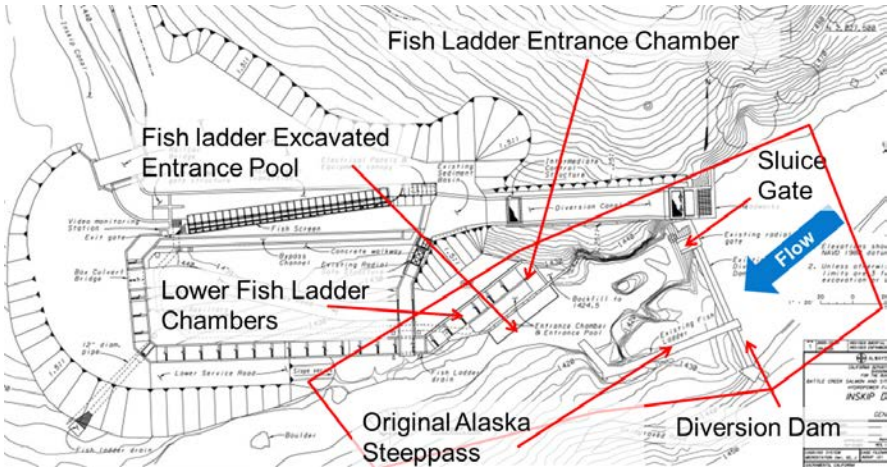


Figure 3. 1:8 scale physical model of Inskip Diversion Dam and fish ladder entrance chamber.

Comparable results between the model and prototype data is achieved when the ratios of the major forces controlling the hydraulic processes are kept equal in the model and the prototype. Since gravitational and inertial forces dominate open channel flow, Froude-scale similitude was used to establish relationships between the model and the prototype parameters. The Froude number is defined as:

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

Where; v = velocity,
g = gravitational acceleration
d = flow depth.

When Froude-scale modeling is used, the following relationships exist between the model and prototype for the 1:8 geometric scale chosen:

Length ratio: $L_p = L_m * 8$

Velocity ratio: $V_p = V_m * (8)^{1/2}$

Time ratio: $T_p = T_m * (8)^{1/2}$

Discharge ratio: $Q_p = Q_m * (8)^{5/2}$

The 1:5 and 1:8 scale hydraulic models provided an accurate representation of prototype headloss, velocities and turbulence. Air entrainment (white water) was slightly different between model and prototype due to surface tension effects. Sediment modeling of fine particles (smaller than 0.1 mm) was limited due to clay particle attractive forces (Van der Waals) while particle sizes greater than 0.1 mm scale proportionally to their length. Fall velocities of the sediment particles and temporal impacts in modeling sediment prevent direct comparison of sediment transport characteristics between model and prototype. The scale models provided a qualitative assessment of where sediment deposition may occur, but not a quantitative analysis of the deposition depth or a sediment transport capacity for a given flow

rate. The 1:8 model contained hard topography and river bathymetry which is well suited to describe the bedrock channel below Inskip Diversion Dam.

Model Features

1:5 Scale Fish Screen Model

At the head of the model, the flow entered the headbox through a pipe and diffuser. The transition from the headbox to the model was completed with a gradually sloped floor and bullnose piers for the vertical sidewalls. Downstream of the headbox, a headworks gate was modeled with the exception of a gate recess into the floor of the model. The gate recess is needed to prevent river flow into the canal during maintenance operations. This gate seal was not necessary for the physical model. The headworks also has a trash rack that was not deemed necessary to include in the physical model. The prototype trashrack bar spacing dimensions are 9 inches x 18 inches and would not create much headloss unless debris obstructing the openings and was therefore not modeled. Figure 4 and Figure 5 show the model features of the 1:5 scale fish screen model.

The design of the new facility also incorporates an intermediate gate that can be used to create additional headloss between the river and the fish screen to control the water surface elevations. This gate was included in the physical model, and was also installed without a gate recess.

Immediately following the intermediate gate was a sediment basin designed to capture coarse sediment coming in through the headworks gate. To do this effectively, the design incorporated a lower floor elevation (elevation of 1425 feet, versus the diversion canal floor elevation of 1432 feet), and a wider cross sectional area to slow the flow locally and result in sediment deposition. The sluice gate was modified for ease of construction by replacing the existing radial gate with a vertical lift gate. While the coefficient of discharge would differ between the two gate styles, the operation of the sediment sluice is expected to be infrequent, and is not used to regulate flow (i.e. during sediment operations, the sluice gate is opened fully for short durations to clear the accumulated sediment from the sediment basin). Therefore, the gate style of the physical model does not significantly alter the function of the sluice gate.

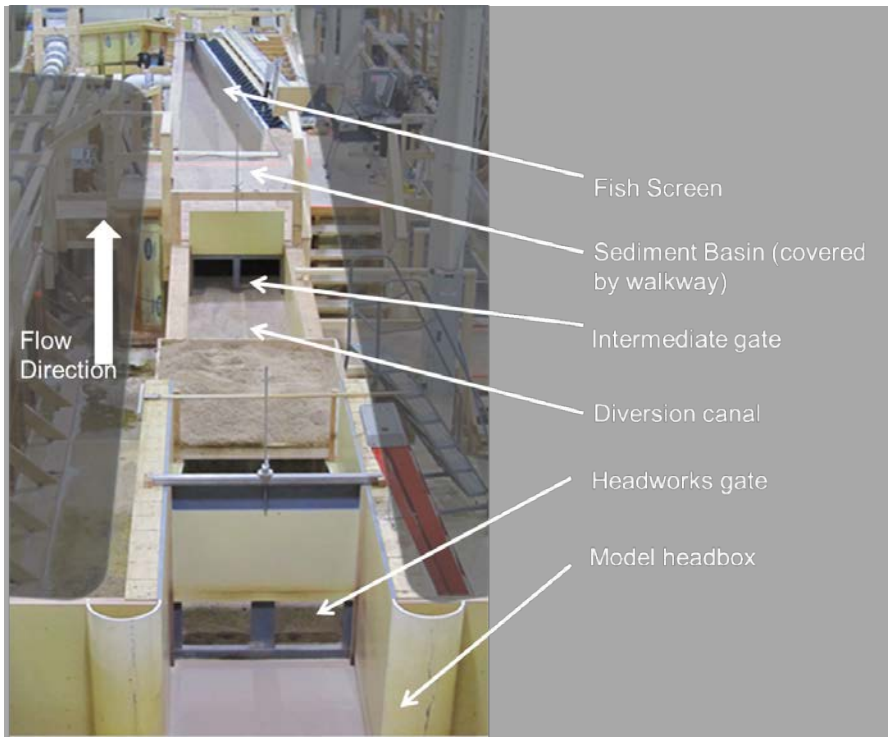


Figure 4. 1:5 scale fish screen model features (looking downstream).

Figure 5. 1:5 scale fish screen model features (looking downstream)

Downstream from the sediment basin was the fish screen structure which included structural support piers between screen panels, but not the horizontal supports for the screen. While the prototype will be constructed with a wedge-wire screen, the physical model fish screen was constructed using perforated plate that matches the design 40% open area. Behind the screen is an additional row of perforated plate (varies from 10-15% open area) that were used to create uniform approach velocities through the screen similar to the louver design for the prototype screen baffle system. These modifications were made for ease of construction and should have negligible impact to the hydraulic performance of the model fish screen.

Porosity of the perforated plate for the screen baffle system was a combination of both 15 percent open (upstream screens 2 through 16) and 12.5 percent open (downstream screens 17 through 29). This baffle configuration produced acceptable results and kept the average velocities nearly uniform across the length of the fish screen. Using perforated plates provided a reasonable estimate of the amount of baffling needed for the screen. While there was a slight increase in approach velocities at the downstream end of the screen that exceeded fish screening criteria for approach velocities, this could have been remedied with a more restrictive baffle plate and can be adjusted to create even approach flow by prototype louver adjustment at the facility.

The fish screen design includes 30 individual screen panel bays with #1 (upstream most) and #30 (downstream most) blanked out. Twenty-six of the bays are 4.5 feet wide, with bays #2 and #29 set at 4 feet wide (prototype) for a total screen length of 125 ft. Initial design for the screen was inclined at 60 degrees from horizontal resulting in a nominal screened area (prototype) of 880 ft^2 and a vertical projection of 762.5 ft^2 at a typical water surface elevation (WSE) of 1438.6 feet. These areas correspond to an average approach velocity of 0.25 ft/s and 0.29 ft/s respectively, not including loss of screen area for structural support members. Figure 6 shows the details of the fish screen sections.

One component of the facility design that was not incorporated into the physical model was the fish screen bypass channel. The proposed bypass is a 4-foot-wide (prototype) channel that is used to pass fish both upstream and downstream when the fish screen is dewatered for maintenance. Since this is a short-term operation that would not be regularly scheduled during periods of likely fish migration, modeling the bypass channel was deemed unnecessary.

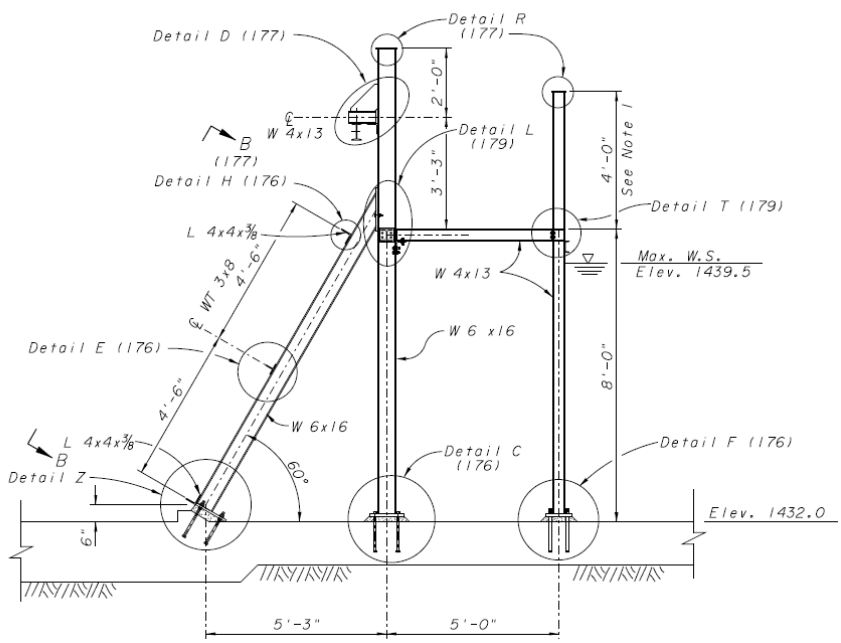


Figure 6. Drawing of the design fish screen cross section.

The screened water (flow that passes through the fish screen) is either diverted down a canal to an offsite hydropower generation facility, or is passed through the AWS pipe and directed towards the fish ladder entrance chamber to supplement the fish ladder attraction flow. Flow for the hydropower canal passes over a pair of tilt gates (i.e., overshot gates) that are each 7 foot wide x 7.5 foot tall (prototype) and drops into the canal and is shown in Figure 7. The AWS pipe is a 42-inch-diameter cement-mortar lined steel pipe approximately 260 feet long (prototype).

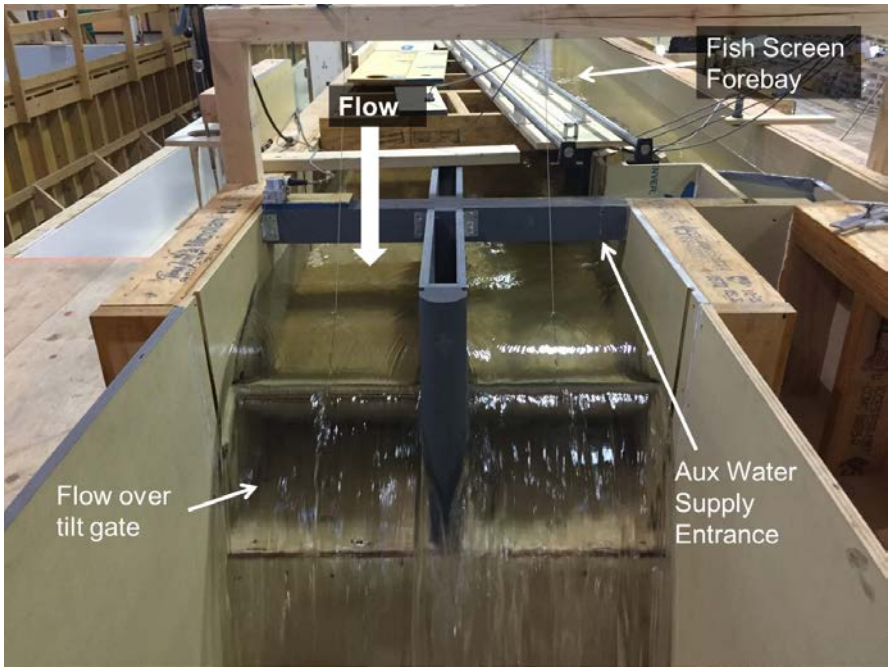


Figure 7. Screened flow through tilt gates and AWS entrance (looking upstream).

Bypass flow that remains in the fish screen forebay passes through a swing gate (controls flow similar to an adjustable width vertical slot weir) into the fish ladder exit chamber and down the fish ladder pools as shown below in Figure 8. At the downstream end of the fish ladder, the flows exit into the multi-gated fish ladder exit chamber and from there into South Fork Battle Creek. All features of the physical model were designed to be geometrically similar to the prototype design. The weirs for the individual fish ladder chambers were designed after the Half Ice Harbor type fish ladder which includes both a single orifice that measures 2 feet x 2 feet and a 5-foot-wide weir above the orifice with a non-overflow wall on the opposite site (prototype dimensions). The fish ladder is designed to pass 39 cfs with a 1.0-foot pool differential, and should be of sufficient size to pass the low flow even during a significant drought period without requiring modification to the size of the orifice opening. The design of the fish ladder weirs can be found below in Figure 9.

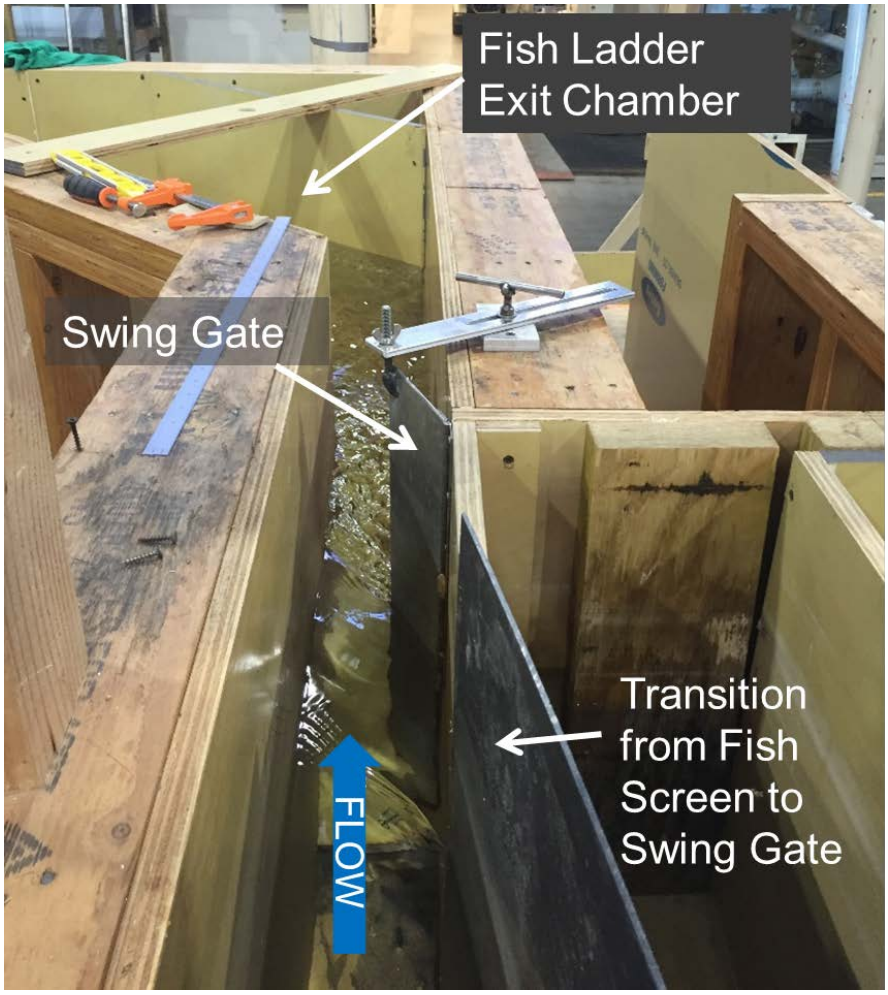


Figure 8. Fish ladder swing gate and exit chamber (looking downstream).

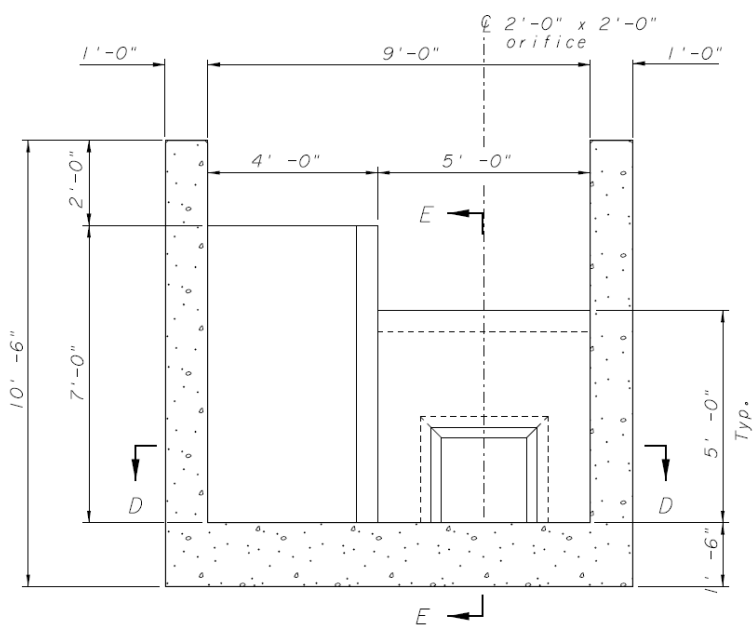


Figure 9. Fish ladder weir detail.

There are 27 weirs total to drop the water surface from elevation 1439 feet to 1411 feet, however only the top 3 weirs (4 pools) before the fish ladder exit were modeled since the hydraulic properties of each weir are identical. Downstream of the 3rd weir, stoplogs are used to create a pool WSE that would be consistent with the backwater created by additional fish ladder weir. Fish ladder flows then dropped into a collection box where flow was measured with a contracted sharp-crested rectangular weir. During validation testing, stoplogs from the 4th pool were removed to confirm there were no impacts to the fish ladder exit chamber WSE or flow through the ladder (and therefore no need to model the connecting fish ladder pools).

1:8 Scale Fish Ladder Entrance Chamber and Diversion Dam Model

Flows enter the model through a pipe and diffuser and through a rock baffle that smooths the flow from the headbox before it enters the model. The model contains a 1:8 scale representations of the diversion dam and sluice gate, the existing Alaska steeppass fish ladder, the fish ladder entrance chamber and excavated entrance pool, and the river topography. Model river topography was constructed with shaped plywood to follow contour lines and a final surface was prepared by wire mesh and mortar. River topography was created from LiDAR survey information on the creek, and extends roughly 100 feet (prototype) upstream of the dam crest and about 500 feet (prototype) downstream of the dam crest. Construction activities performed in 2016 and 2017 by PG&E have filled some of the voids and modified the river channel from what was constructed and tested with the physical model. A view of the model from the dam crest looking downstream can be found below in Figure 10.

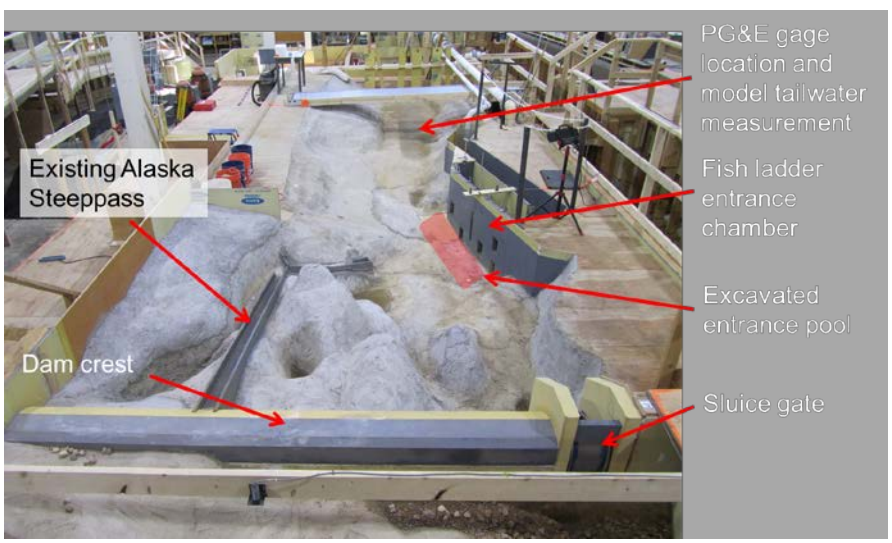


Figure 10. View of 1:8 model looking downstream.

The crest of the dam was scaled to match the existing dam with the exception of the radial sluice gate located near the right abutment. An existing gate that matched the dimensions very closely was used in place of a scaled prototype gate. In addition, the downstream face of the dam which is constructed out of masonry blocks was not modeled since flow control will occur at the crest of the dam (for overflow) or downstream (for river channel flow). The dam was modeled with the originally constructed Alaska steeppass fishway since the presence of the concrete walls will contribute to the flow patterns downstream of the dam, and demolition of the concrete walls is not currently planned during construction of the new facility. Internal steel baffles of the Alaska steeppass are planned to be removed during facility construction, and were therefore not included in the physical model. At the crest of the

dam, the notch that controls flow down the current Steeppass was not modeled since the construction contract includes filling of this area to create a uniform crest.

On the right bank of the river channel approximately 100 feet downstream of the dam crest is the planned location for the fish ladder entrance chamber. It is a structure that contains six gates set at different elevations to allow control of the WSE inside the entrance chamber, and allow passage of adult fish upstream, as well as downstream passage of smolts. The multi-level gates were designed to provide many options for migrating fish depending on if the species prefer orifice or free surface flow. The fish ladder entrance chamber was modeled to match the design of the new facility, with the exception of some of the gate control mechanisms. Initial design for the entrance chamber has a motor operated control gate on Gates A, C and F while Gates B, D and E will have stoplog slots to close gates B and E during normal operation while gate D remains open. Gates in the physical model were constructed to all have a closure mechanism to allow testing of different gate operation and control. Figure 11 and Figure 12 show the design elevations of the original fish ladder entrance gates and the physical model construction, respectively.

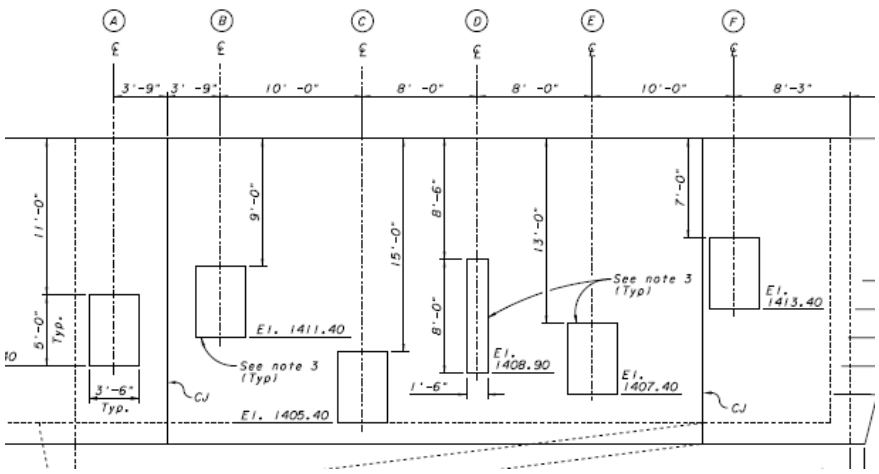


Figure 11. Original elevations of fish ladder entrance chamber gates.

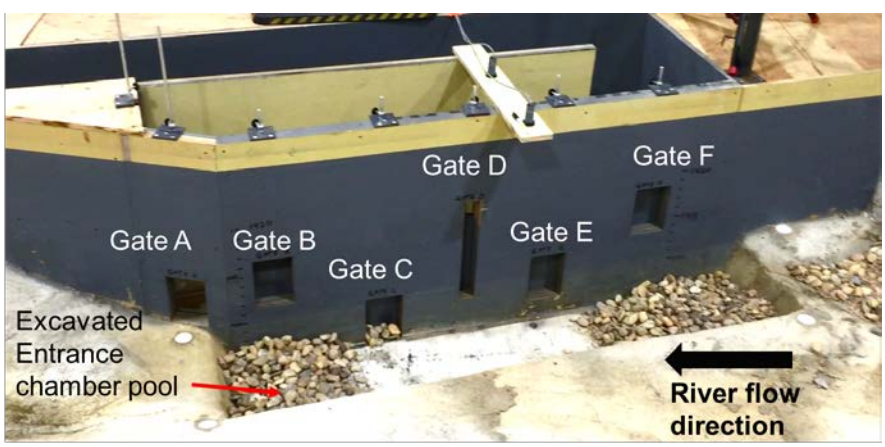


Figure 12. Physical model construction of fish ladder entrance chamber.

Inside the fish ladder entrance chamber, flows coming down the fish ladder meet with AWS flows coming up through a floor diffuser. The elevation of the fish ladder entrance chamber is 1405.4 feet, with a recess below the diffuser at an elevation of 1401.4 feet for the AWS pipe to enter and distribute flows. Flow rates for the fish ladder are 39 cfs, and up to 148 cfs additional flow can be supplied by the AWS resulting in a maximum flow rate through the fish ladder entrance chamber gates to the river of 187 cfs. The AWS has a gate at the outlet to adjust the flow rates between 0 and 148 cfs which will allow the fish ladder entrance chamber to supply the river channel with a minimum of 10% of the total river channel flow.

Outside of the fish ladder entrance chamber is an excavated entrance pool that is used to provide a minimum depth in the river channel for migrating fish. It was originally designed to span the straight wall length of fish ladder entrance chamber (prototype 48 feet long), extend a distance of 9 feet (prototype) out into the river channel, and match the fish ladder entrance chamber's invert elevation of 1405.4 feet.

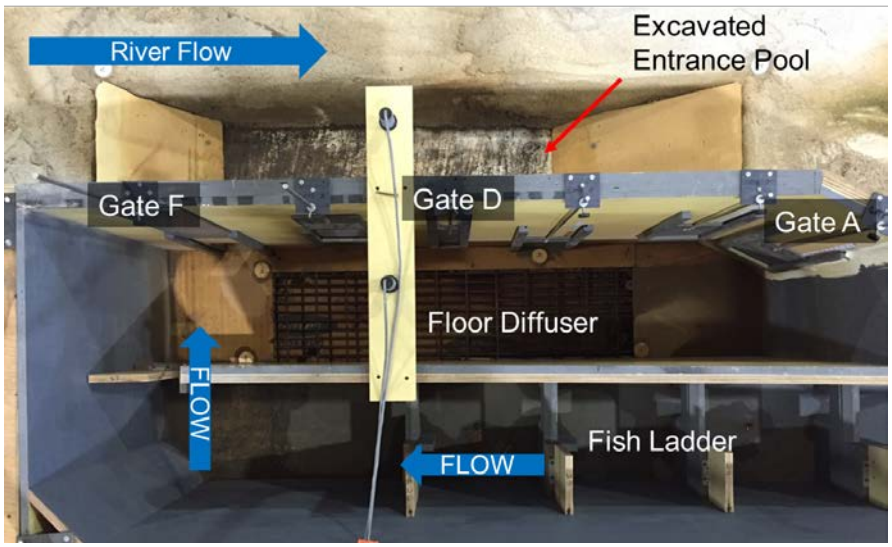


Figure 13. Plan view of fish ladder entrance chamber following modifications.

Downstream of the fish ladder entrance chamber, approximately 300 feet of the river channel topography was modeled to allow accurate river tailwater. Water surface elevations were manually adjusted with tailboards to match results from the Sedimentation and River Hydraulics two-dimensional hydraulic model SRH-2D Version 2 (Reclamation 2016) at approximately the location of the PG&E staff gage. In the physical model, a piezometer tap was placed at the bed elevation at this location. The tap supplied water to a stilling well that allowed a stable WSE to be recorded. The physical model was able to match the tailwater information predicted by the SRH-2D model at the PG&E staff gage location. During model calibration, it was discovered that the WSE in the channel adjacent to the fish ladder entrance chamber was insensitive to any tailwater changes further downstream due to a hydraulic control created at the narrowest spot of the channel between the downstream edge of the fish ladder entrance chamber wall and the left bank as shown below in Figure 14.

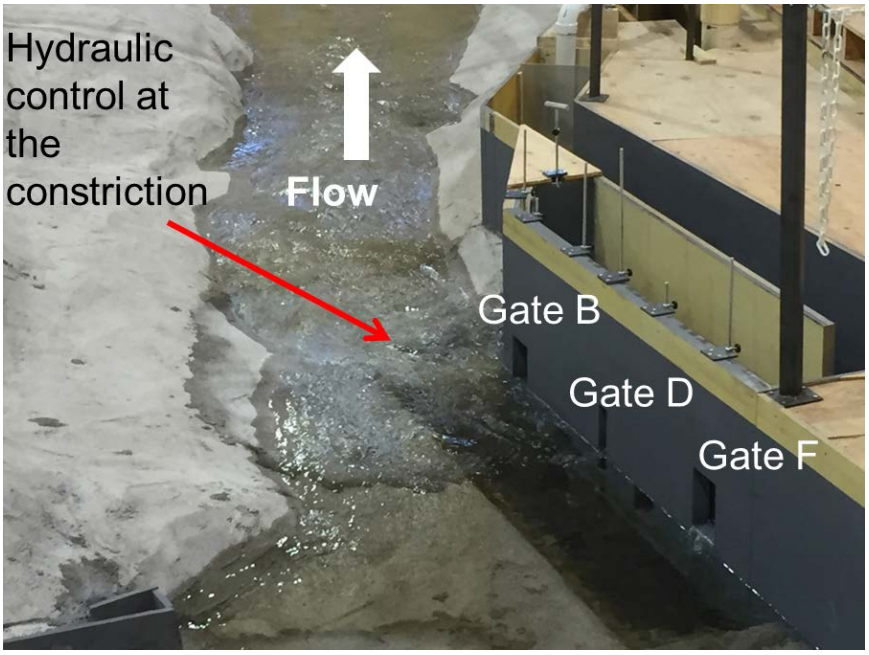


Figure 14. View looking downstream of the hydraulic control created by channel constriction.

Instrumentation

1:5 Scale Fish Screen Model

Screen approach (perpendicular to the screen face) and sweeping (parallel to the screen face) velocities were measured in front of the screen using a Nortek three-dimensional acoustic Doppler velocimeter (ADV). The ADV was mounted to a traversing system that travels parallel to the screen face to maintain the sampling location at a constant distance from the screen face as shown in Figure 16. Due to the size of the probe head and the model scale, point velocities were measured approximately 1.5 inches (model) off the screen face or 7.5 inches (prototype) which is further from the screen than the specified NMFS approach velocity criteria of 3 inches from the screen face (NOAA, 2008).

Initially, velocities were measured at four different elevations and three different lateral locations on each of the 30 fish screen panels as shown in Figure 15. The vertical locations were selected to provide a recorded screen velocity as near the base of the screen as possible, and 3 locations between the base of the screen and the WSE. Lateral spacing was assigned to capture one quarter of the screen width. Commands to locate the velocity probe at each location was programmed into a stepper motor controller to ensure positional accuracy and repeatability. Velocity measurement locations were identical for all screen bays, with the exception of screens #2 and #29 which were 0.5 foot narrower than all other screens. For these locations, the sampling elevations matched, but the lateral spacing was adjusted to maintain one quarter of the screen width. During testing, an internal Reclamation design review resulted in changing the operational WSE of the fish screen forebay from 1439.5 to 1438.6 resulted in the inability to collect samples at elevation 1437.83 due to the velocity probe being out of the water. The remaining elevations were sampled for consistency with earlier test results.

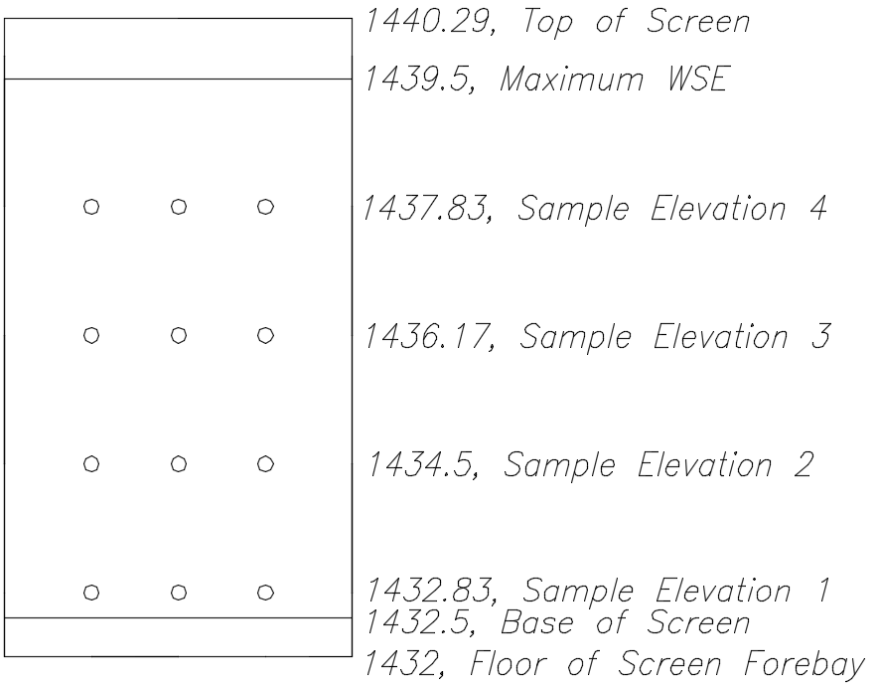


Figure 15. Screen velocity measurement locations (circles indicate sampling locations).

Velocity samples were recorded for 30 seconds at 25 Hz sampling frequency for each sampling location and were processed with WinADV Version 2.031 (Reclamation 2016) to obtain velocity components of the sweeping velocity (Vx), approach velocity (Vy) and vertical velocity (Vz). Velocity values that had correlations less than 70% or rapid accelerations were filtered out during processing (typically 8% of the ADV samples collected were filtered out). In addition to the individual points collected per screen, a uniform speed traverse program was created to compare point measurements with moving traverse measurements. The velocity probe was placed at a given elevation and allowed to traverse up and down the screen to measure 3D velocities. Since both directions were traveled, the sweeping velocity was averaged to remove the speed of the traveling cart. A processing WinADV flag file was created to use the known distances between the screens to select a time span for velocity samples that corresponds to a specific screen.

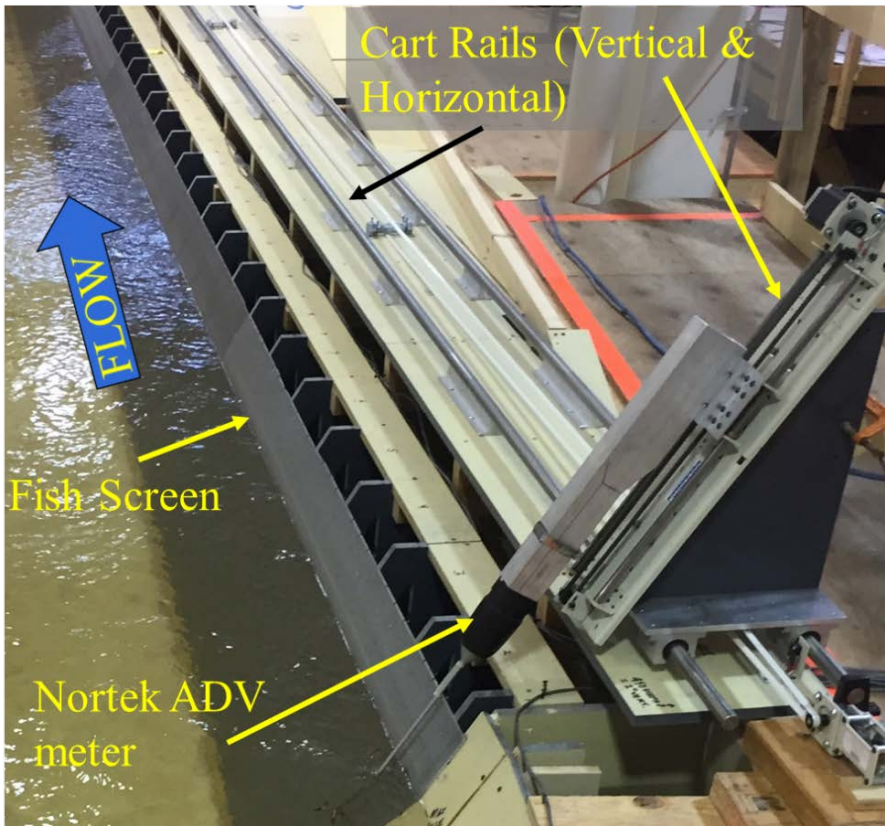


Figure 16. Nortek ADV and traversing rail system.

Gate position sensors were installed on the headworks, intermediate and tilt gates to monitor percent open and a digital output was displayed on a computer screen via DASYLab® data acquisition software (National Instruments 2016). The sediment basin sluice gate was marked on the side to measure the gate opening. Water surface elevations were recorded at many locations both manually via point gages in stilling wells, and with Massa Products Corporation's acoustic water level sensors (Massa). Water level monitoring locations were the upstream of the screen forebay, downstream of the screen forebay, the fish ladder exit chamber (between the swing gate and the upper-most weir), and the water surface elevation of the screened diversion water just upstream from the tilt gate.

Flow to the physical model was supplied by a permanent laboratory pump and water measurement was performed by calibrated venturi meters. Flows exiting the fish ladder chambers were measured by a contracted sharp-crested rectangular weir and calculated by measuring the head over the crest by a Massa acoustic level sensor. Flows leaving the system through the AWS pipe were measured using a Controlotron clamp-on acoustic flowmeter. Flow passing over the tilt gates was calculated by subtracting the sum of the AWS and fish ladder flows from the total model inflow.

1:8 Scale Fish Ladder Entrance Chamber and Diversion Dam Model

Water surface elevations were measured at various locations in the physical model. Massa acoustic sensors were used upstream of the dam, at a location just upstream of Gate D for both river WSE and fish ladder entrance chamber WSE and in a stilling well that matches the current PG&E staff gage location. Additional stilling wells were installed to measure the WSE of the fish ladder pools number 22,

24 and 26. Manual velocity measurements were recorded with a SonTek FlowTracker handheld ADV to assess the vertical velocity component of the AWS diffuser.

In the physical model, the Massa acoustic sensors for the fish ladder entrance chamber and river WSE were installed just upstream of gate D to ensure that the surface attraction flows at gate D represented 1.0 foot of WSE differential. Due to the flows that exited the fish ladder entrance chamber at this location, there was stagnation in the WSE of the river channel which resulted in a drop of 2.0 feet (prototype) for a fish ladder entrance chamber flow of 187 cfs and a total river flow of 1870 cfs as shown below in Figure 17. In addition to this drop, there was an additional nearly 2.0 feet (prototype) of drop in the WSE at the hydraulic control at the downstream end of the fish ladder entrance chamber. At Gate A, this resulted in a total differential WSE of approximately 50” prototype for the above flow condition.

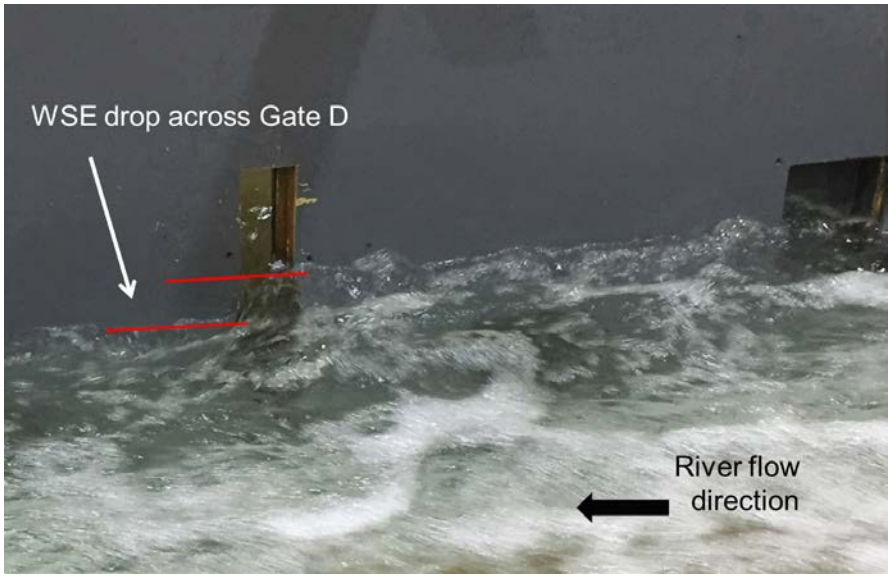


Figure 17. Water surface elevation drop across Gate D due to stagnation.

Model Modifications

1:5 Scale Fish Screen Model

Following the initial physical model tests in the 1:5 scale fish screen model, a few modifications were necessary to improve the hydraulic performance. Modifications to the sediment basin, fish screen, fish ladder exit chamber and AWS entrance were investigated in the physical model.

Flow transition from the design sediment basin was resulting in high amounts of turbulence in the flow passing the upstream portion of the fish screen. Figure 18 shows a design drawing of the original (black lines) and the modified (turquoise lines) sediment basin design. There were three major areas (circled in red) that were modified in the revised design. The right side wall of the initial design expanded outwards, then had a sharp contraction to start the transition between the sediment basin and the fish screen. The second modification was to the sharp angle created from the approach for the sediment basin sluice gate and the left side vertical wall of the fish screen forebay. Finally, the floor of the sediment basin that is recessed by 7 feet (prototype) from the diversion canal invert and the fish screen forebay

elevation had an angled transition that went from the right side towards the left side (in plan view) and was angled downstream (in profile view). Combined, these features resulted in significant flow separation and turbulence that was evident in the standard deviation of the velocities in the upper portion of the fish screen. In addition, these features added some complexity to the concrete form work that would add time and cost to the construction of the facility.

Modifications to the sediment basin are circled in red in Figure 18, while the new outline is shown in turquoise. Three major changes are to connect the diversion canal right side wall directly with the side wall that forms the transition to the fish screen, chamfer the wall between the sluice approach channel and the left fish screen forebay wall, and create a vertical transition from the floor of the sediment basin to the fish screen floor elevation. The alignment of this vertical transition was also altered from being angled to being perpendicular to the flow direction through the sediment basin.

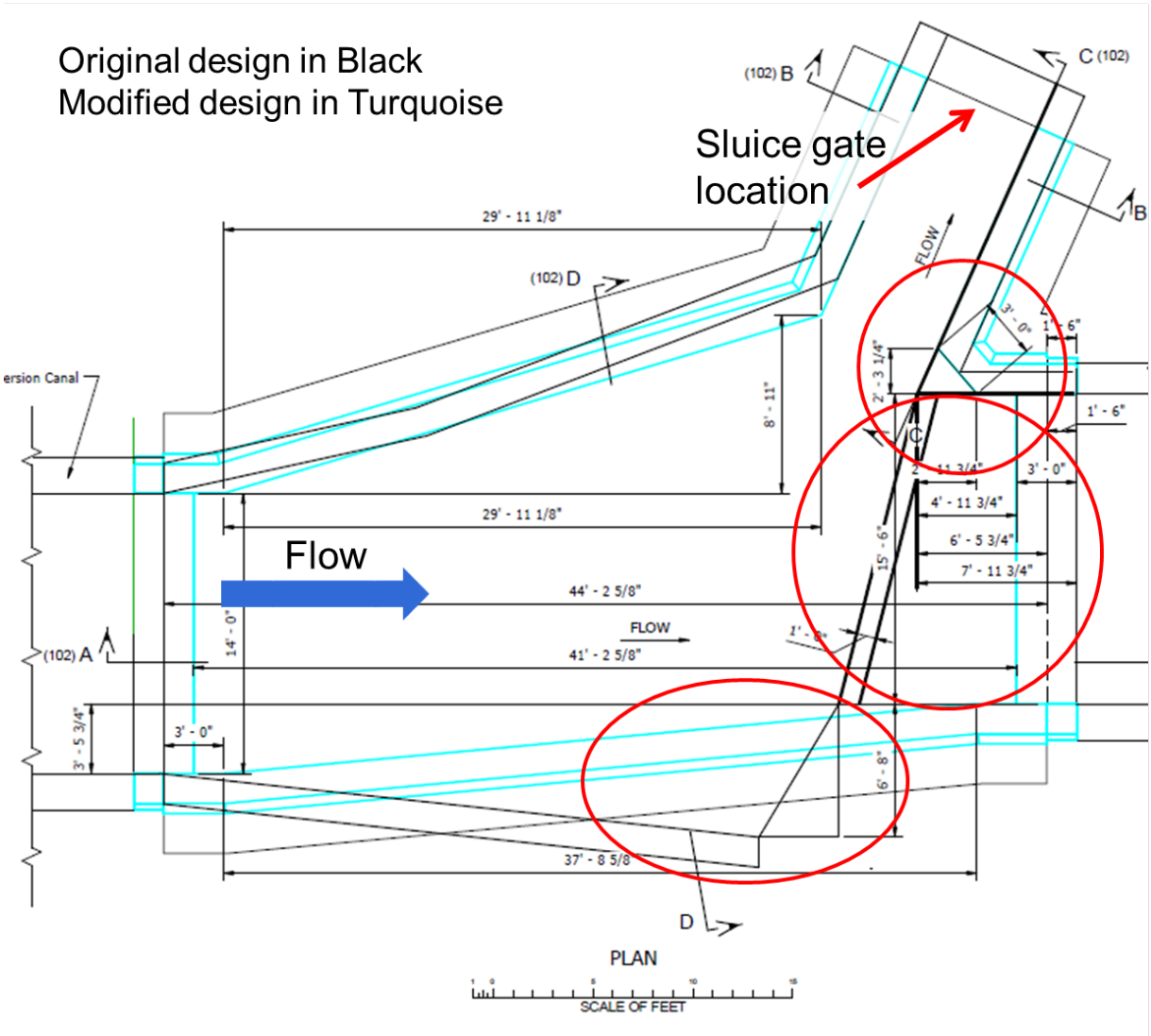


Figure 18. Sediment basin modifications drawing

During a Reclamation design review, it was discovered that some of the mechanical connections for the fish screen panels, structural supports and related equipment had interference issues with the 60 degree screen angle. In addition, maintenance concerns with the traveling brush screen cleaning system at other

PG&E projects with 60 degree screen angles supported changing the screen angle. Eagle Canyon Diversion has a fish screen angle of 83 degrees from horizontal which has reportedly worked well, therefore the revised design was set to match that angle. Changing the screen angle allows the mechanical connections to be made without risk of interference in the construction of the fish screen, as well as reducing maintenance on the traveling brush cleaning system. Photographs of the initial design (Figure 19) and the modified design (Figure 20) showing the fish screen forebay can be found below. A drawing of the revised screen design can be found below in Figure 21. With the changed fish screen angle, the upstream and downstream transitions were also modified to ensure a smooth flow transition.

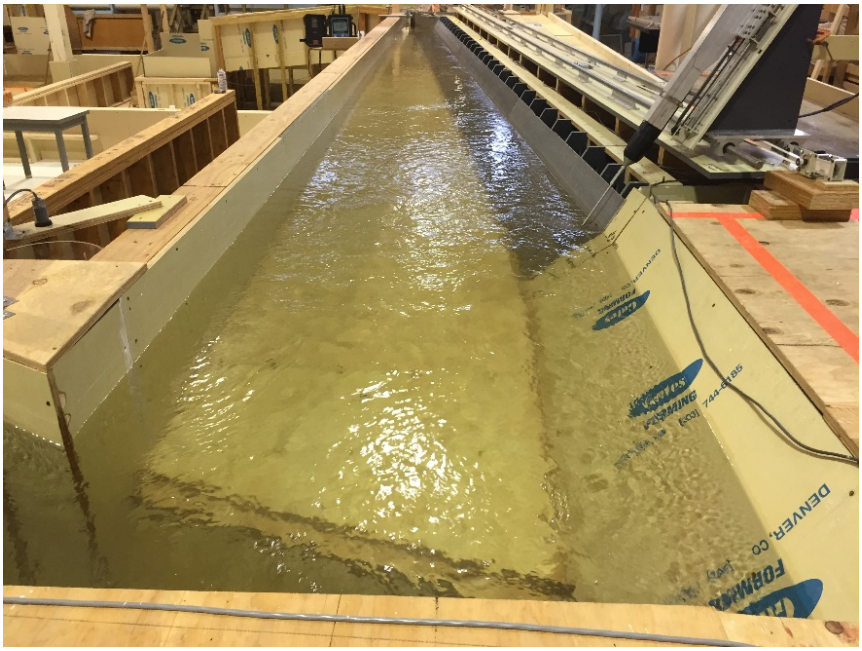


Figure 19. View looking downstream of initial screen forebay design layout with the fish screen at a 60 degree angle.

Figure 20. View looking downstream at the modified screen forebay with the fish screen at an 83 degree angle.

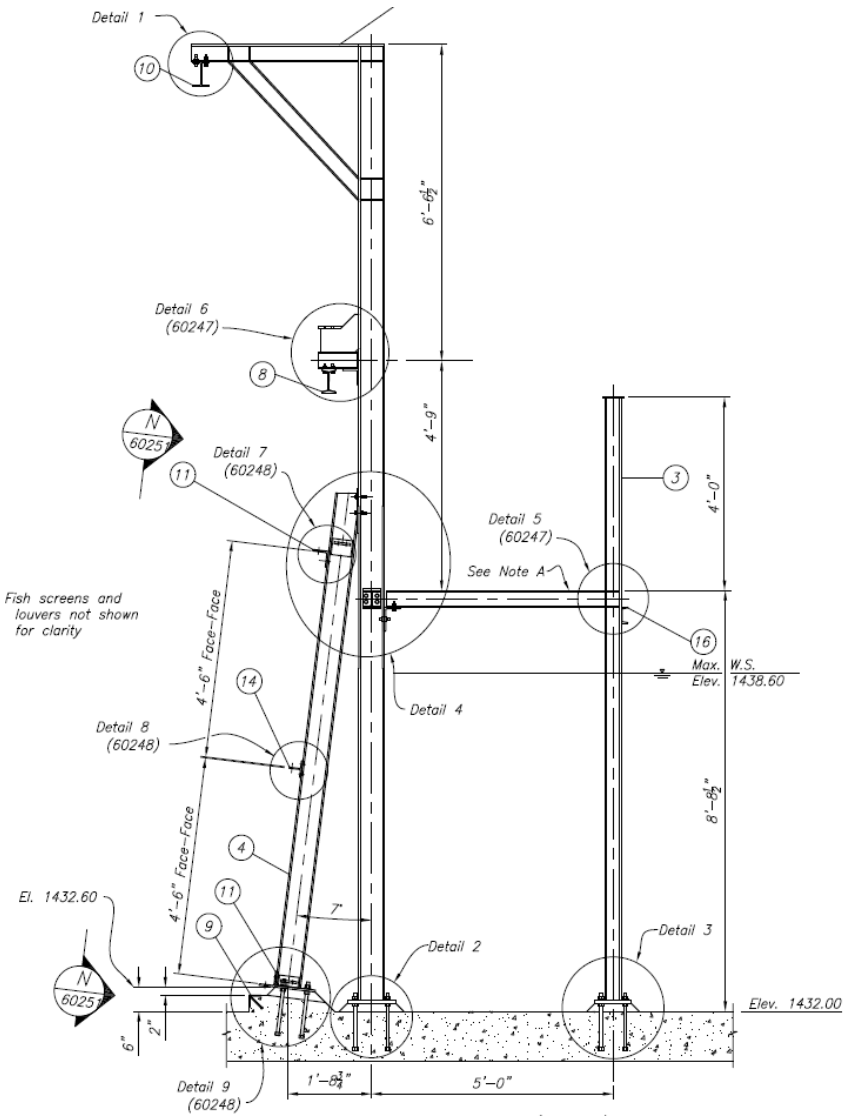


Figure 21. Revised fish screen design drawing, section view.

At the fish ladder exit (the upstream most portion of the fish ladder), there was a large exit chamber that transitions between the bypass channel swing gate and the uppermost weir of the fish ladder. At this location, the angular expansion and initial design of the chamber resulted in a large eddy that allowed fine sediment to deposit, created turbulence that may interfere with the fish ladder observation window and may provide a holding area for predatory fish. To remedy this, the area of the expansion was reduced by modifying the side walls as shown in Figure 22.

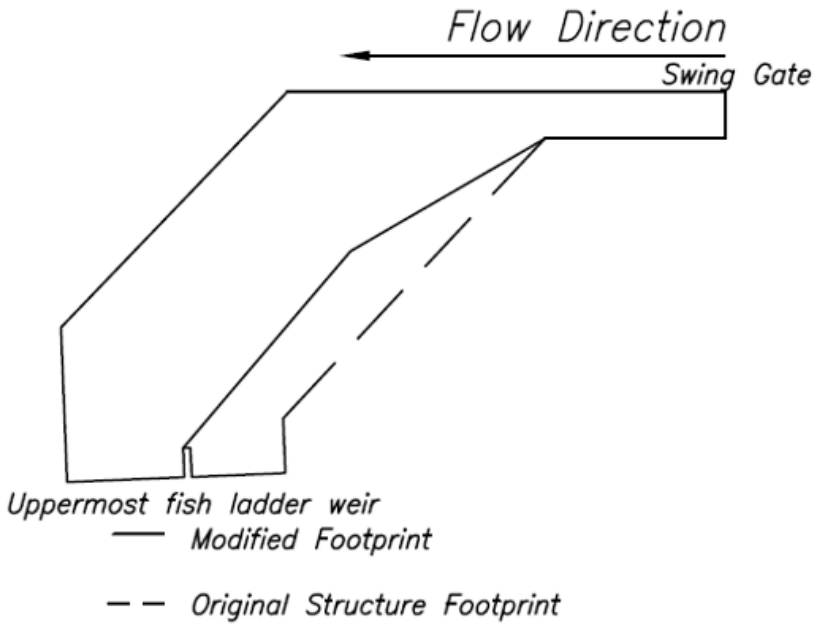


Figure 22. Fish ladder exit chamber modification.

The initial AWS intake design included a horizontal trash rack that was set to match the elevation of the concrete floor at this location just upstream of the left tilt gate. During a Reclamation design review it was determined that this created a potential safety concern since a person could become pinned against the rack which would be approximately 6 feet underwater. Therefore, the trash rack was redesigned to a vertical rack. Furthermore, from initial model tests, there was a concern of vortex formation as the flow into the auxiliary pipe intake turned 90 degrees from the tilt gate streamlines. The new trash rack was designed with 3/8- inch bars with 1inch spacing to straighten flow as it entered the auxiliary pipe entrance. Modifications to the trash rack design greatly alleviated the vortex formation in the physical model and is not expected to exceed a small surface swirl and an unstable dye core vortex. This is a significant improvement over the full air core vortex that was observed with the initial design. Figure 23 shows the AWS pipe entrance with the initial design and with the modified trash rack. Note the deflection of the water surface at the upstream side of the trash rack as water is entering through the bars of the trash rack.

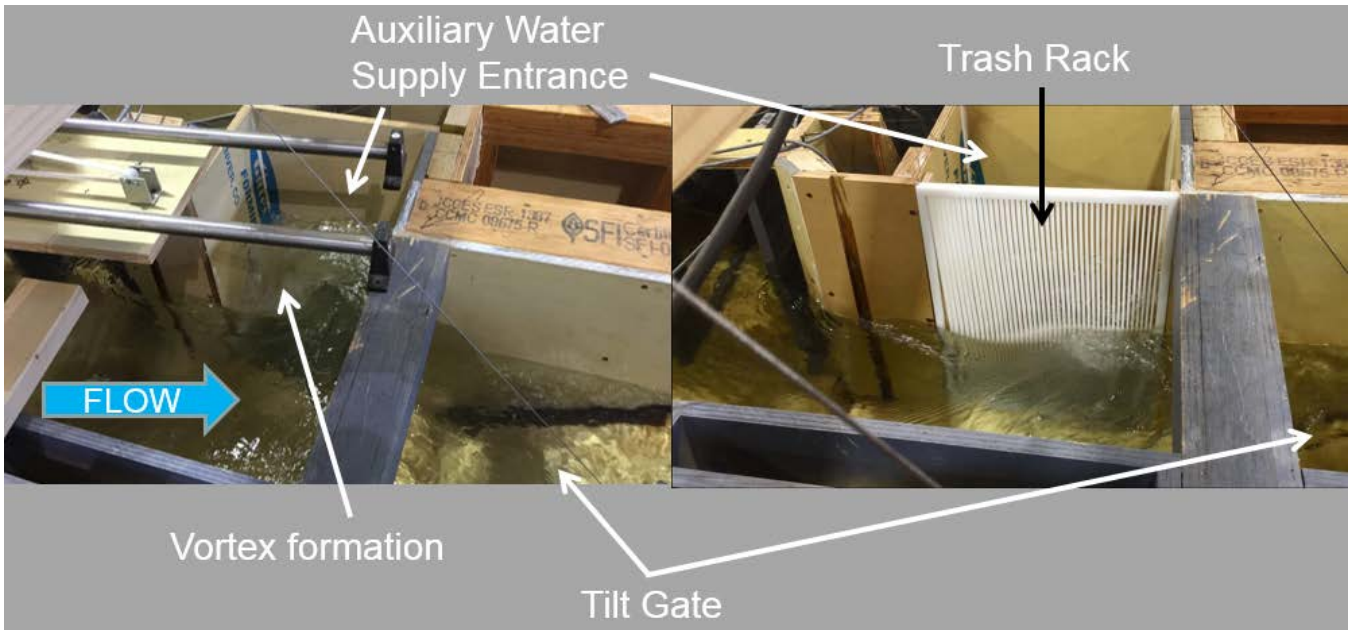


Figure 23. AWS entrance. The left side image is the original design and the right side image is the modified trashrack design.

1:8 Scale Fish Ladder Entrance Chamber and Diversion Dam Model

Following initial tests on the 1:8 scale fish ladder entrance chamber and diversion dam model, a few modifications were required to optimize the functionality of the new facility. Modifications included changes to the gate elevations of the fish ladder entrance chamber, the excavated entrance pool and the non-overflow portion of the fish ladder weirs.

The original design elevations of the fish ladder entrance chamber gates can be found in Figure 11. During tests to determine potential impacts of sediment coming down the fish ladder, it was observed that if gate F were located at the invert of the entrance chamber, sediment would likely be able to pass out of the structure to the excavated entrance pool even during flows of only 39 cfs. With the original gate F located 9 feet (prototype) above the floor elevation this gate was above the water surface for flows below flood stage and therefore any sand that traveled down the fish ladder would have to exit at a location further away from the final fish ladder pool. This resulted in a deposition pattern that angled towards the further downstream gates as shown below in Figure 24. While flow could be passed through Gate E, its invert is 2 feet (prototype) above the floor of the entrance chamber and would result in sediment accumulation up to that depth. Therefore, the invert elevation of Gate F was modified to match the floor elevation of 1405.4 feet which allows sediment to pass straight from the last fish ladder orifice directly out to the excavated entrance pool. Figure 25 shows results after an identical test with the modified gate F which has allowed a large amount of the sand coming down the fish ladder to pass out of the excavated entrance chamber. While a significantly larger amount of sand exited through modified Gate F, some sand will still traveled towards the downstream gates since Gate D is always open for surface attraction flow.

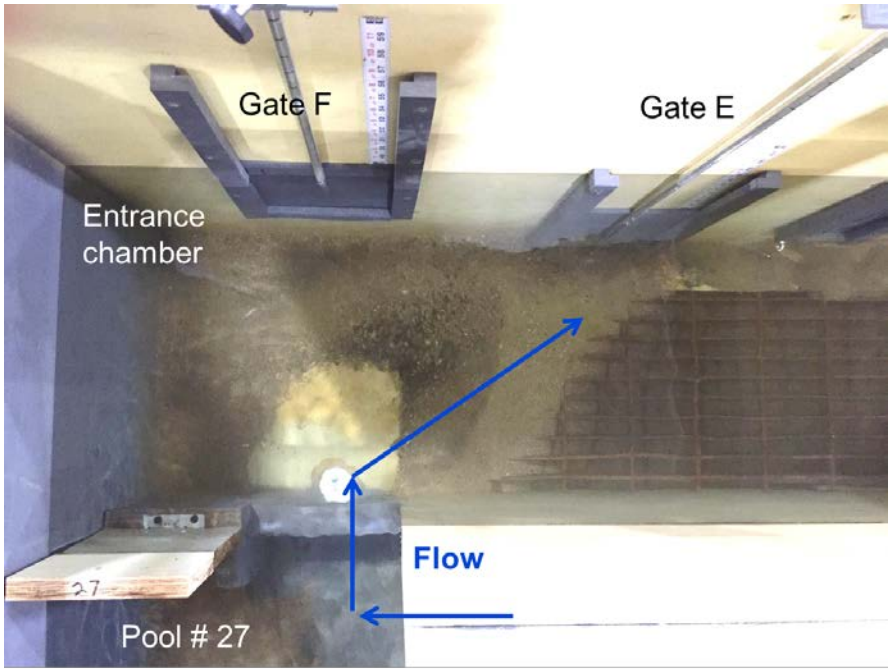


Figure 24. View of sediment deposition with 39 cfs total flow and original design.

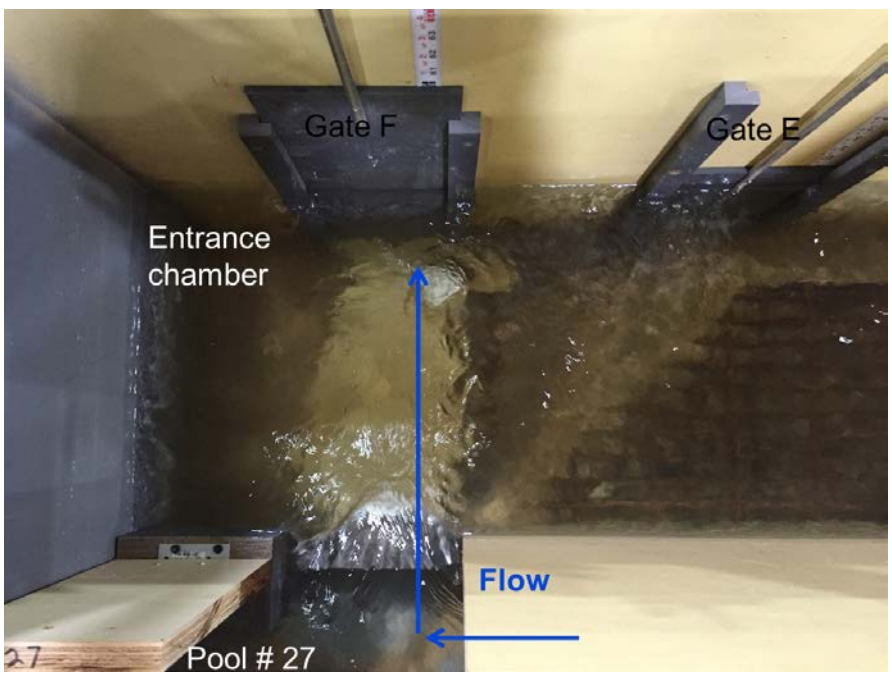


Figure 25. View of sediment deposition with 39 cfs total flow and modified Gate F.

To ensure that the modified design still allowed fish passage at multiple water surface elevations, gate E was relocated to an elevation of 1413.4 feet which matched the invert elevation of the original gate F.

Gate D was also modified to ensure that a surface disturbance was created for the full flow range of the design to attract fish to the entrance. The design top elevation of gate D was 1416.9 feet, and was found

to be submerged (and under orifice control) for flows that exceeded 1000 cfs. To ensure that surface attraction was provided at the design maximum flow of 1870 cfs, the top elevation of gate D was modified to be at elevation 1421 feet. These changes can be found below in Figure 26.

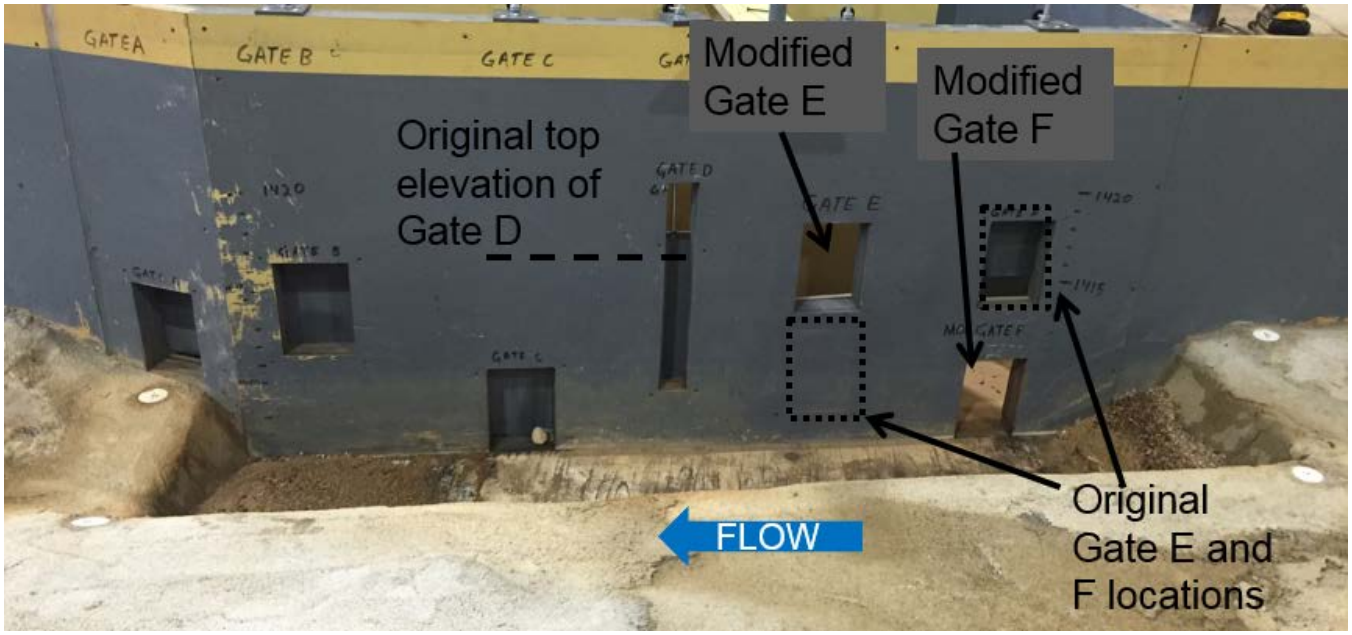


Figure 26. Modified gate locations of fish ladder entrance chamber.

Due to the backwater elevation from the river channel at the fish ladder entrance chamber, some of the fish ladder weirs were modified to extend the non-overflow portion of the weir. Weirs that were impacted were #21-#27 which had a top elevation below elevation 1420 feet. Boards that matched the width of the Half Ice Harbor non-overflow portions of the weir were installed to bring the top elevation to 1420 feet as shown below in Figure 27.

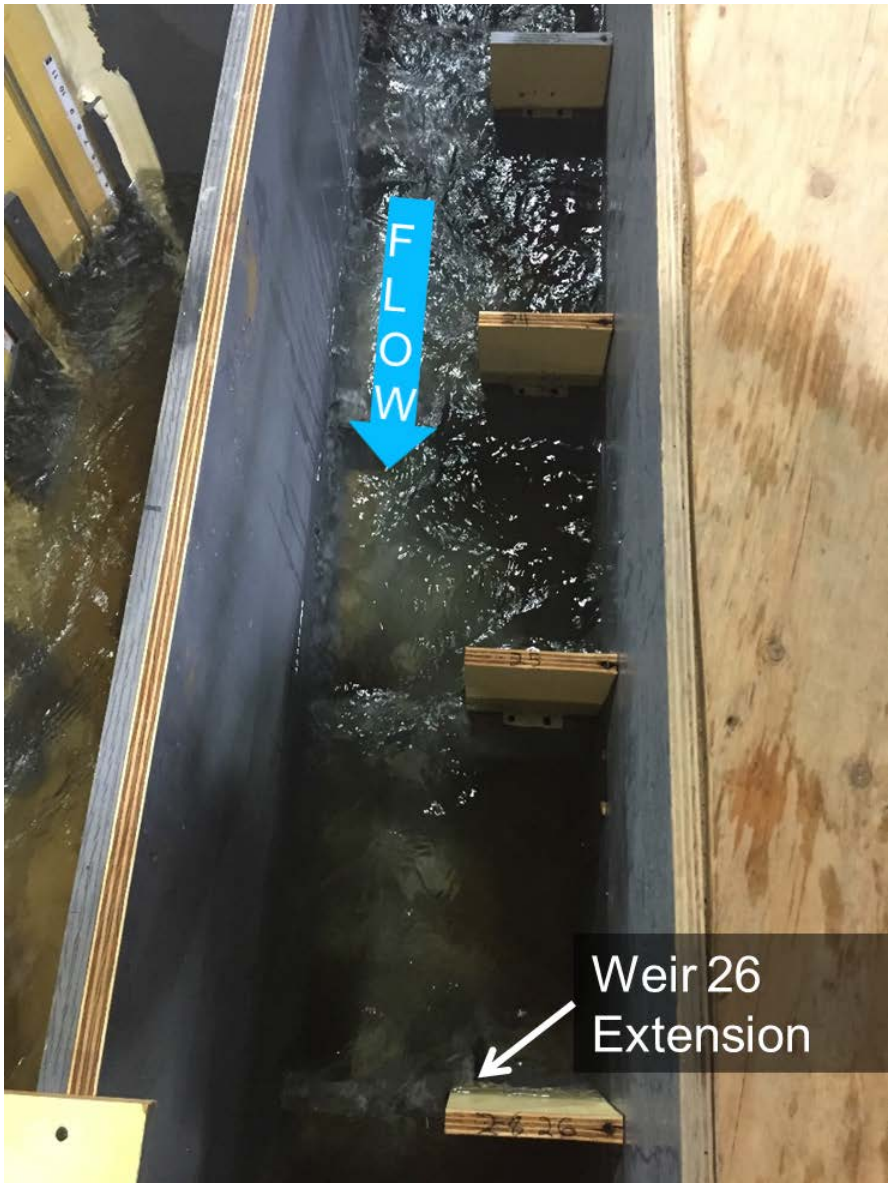


Figure 27. Vertical extension of non-overflow weir walls.

Modifications were also made to the excavated entrance chamber pool on the channel side of the fish ladder entrance chamber. Originally, the excavation was designed to span the full length of the entrance chamber, and was set to have vertical (or near vertical) transitions from the invert elevation of 1405.4 to the existing grade at the upstream, downstream and river side walls. The modified design narrowed the width of the excavated entrance pool and revised the transition from elevation 1405.4 to existing grade. At the upstream end, the modified excavation started approximately 1 foot upstream of the Gate F location, and was set at a 0.25:1 (H:V) slope until it met the existing river channel at approximately 1411 feet. The downstream end had a more gradual slope of approximately 2:1 (H:V) and started its rise 1 foot downstream of Gate C until it met the river channel elevation. The river side wall of the excavation was sloped back at 0.25:1 (H:V), and was modified to have a slightly narrower bottom width of 7.0 feet. A photo of the modified excavated entrance pool can be found below in Figure 28. These changes resulted in approximately two-thirds of the originally planned excavation and saves both time and cost for the project.

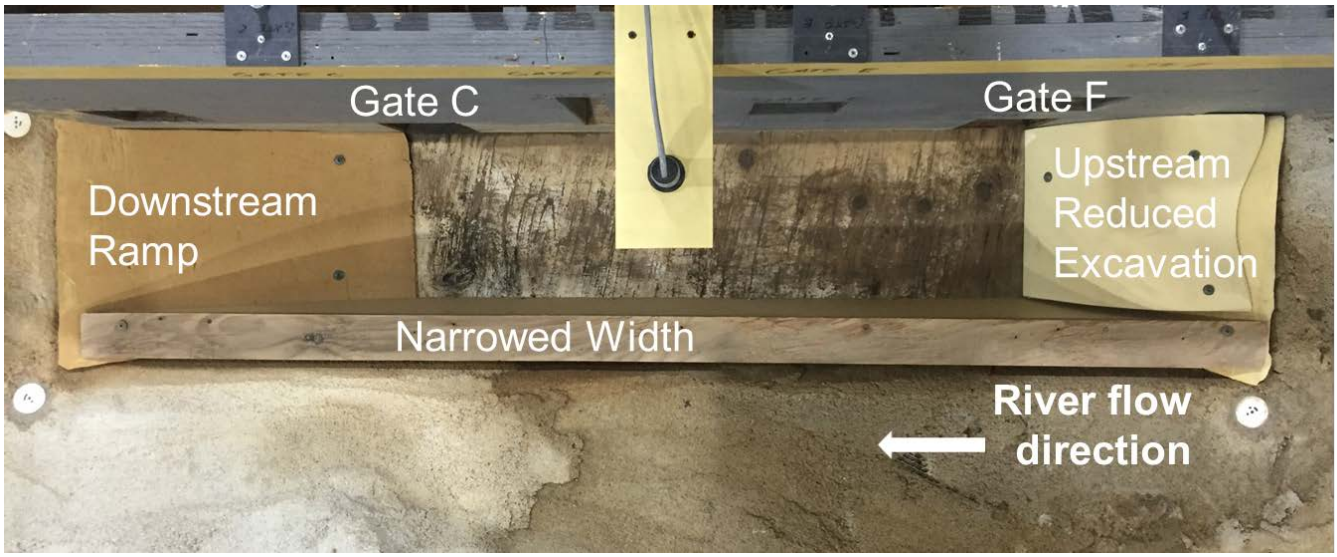


Figure 28. Plan view of modified excavated entrance pool.

Model Tests and Results

1:5 Scale Fish Screen Model

Fish Screen Performance Test Results

An initial test of fish screen hydraulics was conducted without baffling to show approach velocity patterns without any baffling. As shown in Figure 29, the approach velocity distribution along the screen face shows a strong increase both vertically (approach velocity is higher near the water surface) and laterally (approach velocity is higher at the downstream end of the screen).

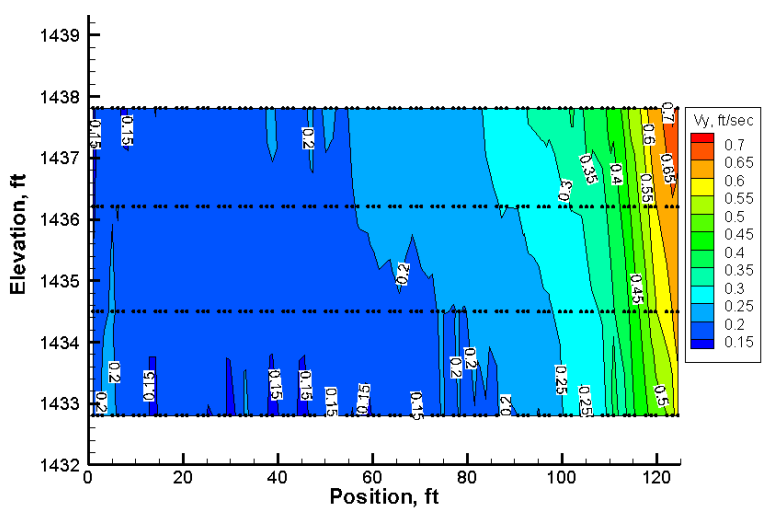


Figure 29. Test 2 showing approach velocities on fish screen without baffle plates (diversion flow of 259 cfs, fish ladder flow of 39 cfs, AWS flow of 55 cfs, and canal flow of 165 cfs). Velocities are scaled to prototype values.

Under the same flow conditions, the fish screen was baffled to 15 percent open area in the upstream region (screens 2 through 16) and 12.5 percent open area in the downstream region (screens 17-29). This configuration of screen baffles resulted in approach velocities across the screen within fish screening criteria of 0.33 ft/s and can be seen below in Figure 30.

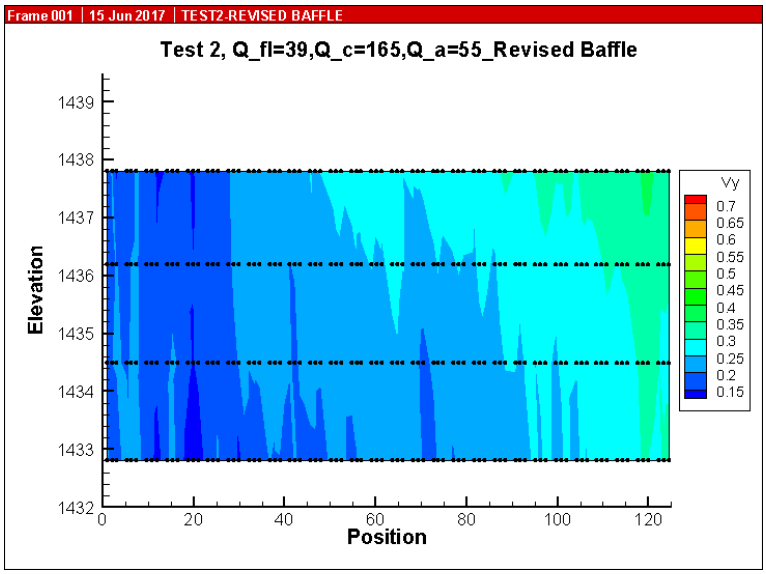


Figure 30. Test 2 showing approach velocities on fish screen with 15% baffles in upstream and 12.5% baffles in downstream plates (diversion flow of 259 cfs, fish ladder flow of 39 cfs, AWS flow of 55 cfs, and canal flow of 165 cfs). Velocities are scaled to prototype values.

Table 1. 1:5 scale model test matrix.

Test #	Diversion flow (cfs)	Fish ladder flow (cfs)	Screened flow (cfs)	Canal flow (cfs)	AWS flow (cfs)	Notes
1	259	39	220	220	0	Maximum Diversion
2	259	39	220	165	55	
3	204	39	165	165	0	
4	187	39	148	148	0	10% of 1/10 ACE flow
5	187	39	148	83	65	
7	151	39	112	112	0	Existing canal typical diversion
8	104	39	65	0	65	
9	39	39	0	0	0	Swing gate sensitivity
10	259	39	220	165	55	
11	259	39	220	165	55	Test 2 with WSE = 1438.6 ft
12	187	39	148	55	93	
13	259	39	220	165	55	Test 2 with staggered baffles
14	242	39	203	55	148	River flows up to 1/10 ACE
15	187	39	148	0	148	Maximum AWS flow

A test matrix was compiled to investigate a range of potential operational alternatives and is detailed below in Table 1. Tests with the original design confirmed there was very little deviation in either approach or sweeping velocities due to different component operation (tilt gate vs. AWS) and differences were more a function of total flow diversion amount. Therefore, testing of the screen modifications were limited to only select tests that spanned the range of potential diversion flows (tests that were not repeated are greyed out in Table 1). Note: Test 6 is not included because the original model construction was only able to produce 109 cfs for the AWS. Test 15 allows the full 148 cfs after the model AWS was reconfigured.

Plots of Test 1 (259 cfs diversion, 39 cfs fish ladder flow, 220 cfs canal flow) which is the maximum diversion of flows through the canal for both the original design at a 60-degree screen angle and the modified design at an 83-degree screen angle can be found in Figure 31 and Figure 32, respectively. Table 2 compares the test results between the original 60-degree screen angle and the modified 83-degree screen angle. Average approach velocities were lower with the original design due to the greater effective screen area at 60-degrees. Sweeping velocity was higher with the modified 83-degree screen design due to the smaller cross sectional area in the screen forebay. Both the sweeping and the approach velocities were found to be more uniform with the modified 83-degree screen angle along the length of the fish screen forebay. Vertical velocities were found to be much smaller with the modified design than the original design. The final two columns of Table 2 contain a summation of the calculated flow volume (by the continuity equation) that was recorded with the screens, and what percentage was recorded versus the theoretical total flow passing through the fish screen. Both designs meet the criteria for both sweeping and approach velocity.

Table 2. Test result comparison between original 60-degree-angle fish screen and modified 83-degree-angle fish screen.

	Screen Angle	Screened Flow (cfs)	WSE (ft)	Approach Velocity (ft/s)	Sweeping Velocity (ft/s)	Vertical Velocity (ft/s)	Measured Screen flow (cfs)	% of expected
Test 1	60°	220	1439.5*	0.23	2.17	0.09	184	84%
Test M1	83°	220	1438.6	0.30	2.75	0.02	204	93%
Test 14	60°	203	1438.6	0.25	2.47	0.11	164	81%
Test M14	83°	203	1438.6	0.27	2.60	0.02	186	92%
Test 15	60°	148	1438.6	0.19	1.91	0.08	128	87%
Test M15	83°	148	1438.6	0.20	2.11	0.01	136	92%

* Test 1 was completed with a higher WSE, and was not repeated for the lower expected WSE

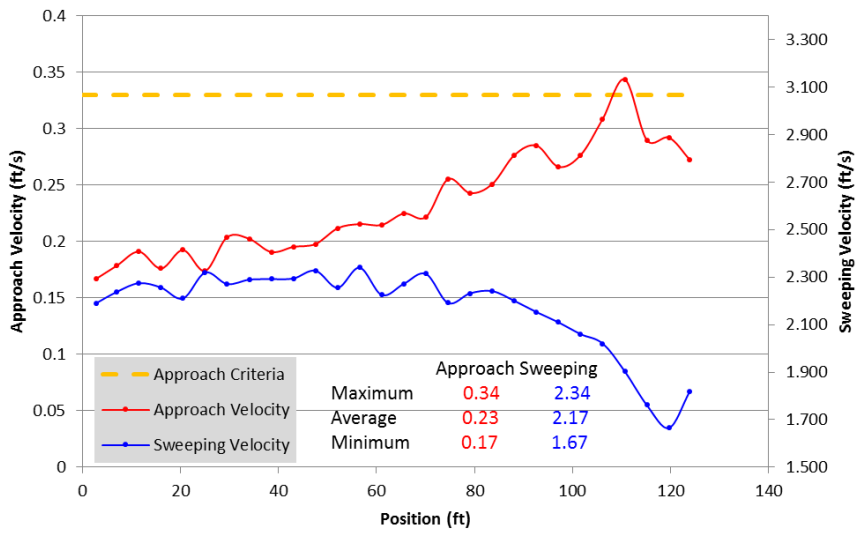


Figure 31. Test 1 original design 60-degree screen performance at maximum diversion (prototype fish ladder flow of 39 cfs, canal flow of 220 cfs, and AWS flow of 0 cfs).

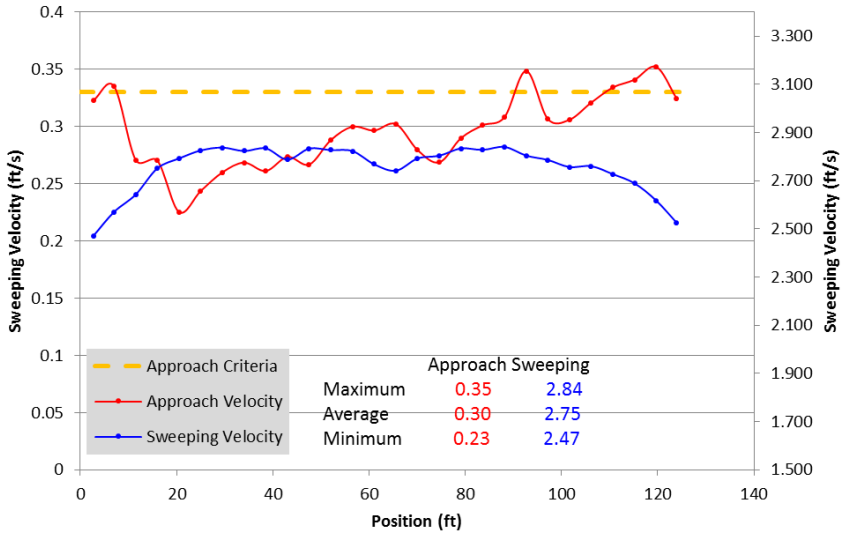


Figure 32. Test M1 modified design 83-degree screen performance at maximum diversion (prototype fish ladder flow of 39 cfs, canal flow of 220 cfs, and AWS flow of 0 cfs).

Additional tests were performed with the normal canal flow of 55 cfs (which assumes the tailrace connector from South Powerhouse supplies 165 cfs to the canal) and the maximum AWS flow of 148 cfs. Plots of the approach and sweeping velocities can be found below in Figure 33 and Figure 34 respectively.

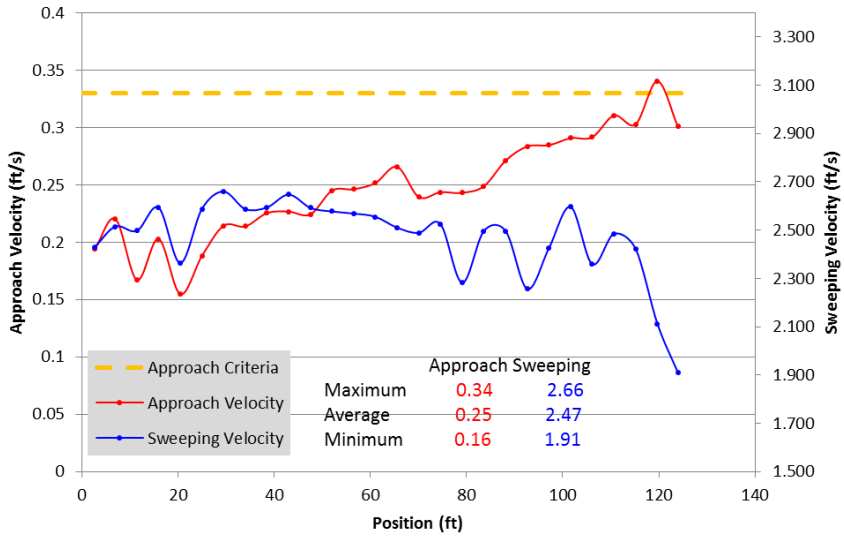


Figure 33. Test 14 original design 60-degree screen performance at normal canal, high AWS operation (prototype fish ladder flow of 39 cfs, canal flow of 55 cfs, and AWS flow of 148 cfs).

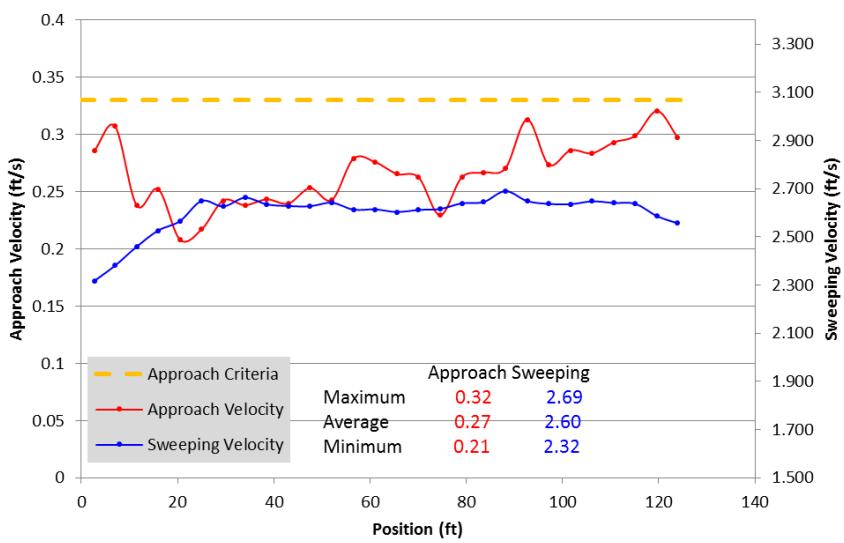


Figure 34. Test M14, modified design 83-degreen screen performance at normal canal, high AWS operation (prototype fish ladder flow of 39 cfs, canal flow of 55 cfs, and AWS flow of 148 cfs).

Swing Gate Rating Curve Results

In addition to measuring the velocity components along the fish screen, a rating curve was created for the swing gate that controls the flow entering the fish ladder.

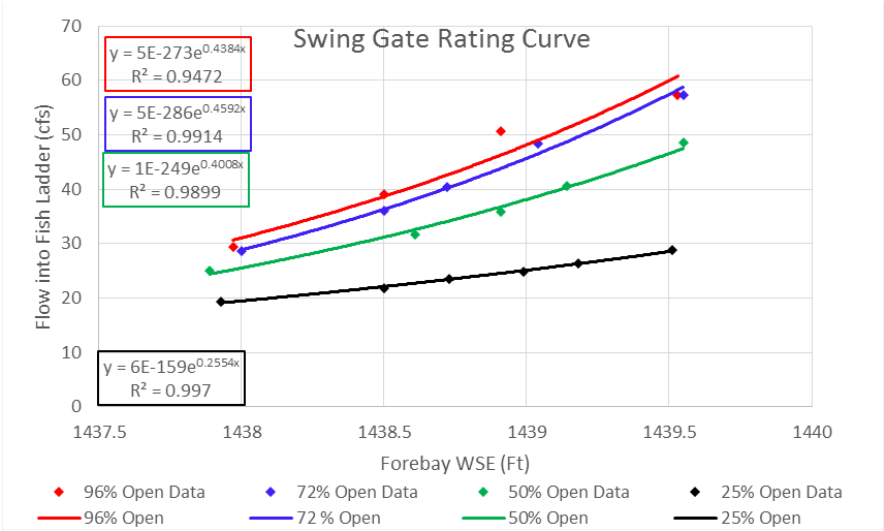


Figure 35. Swing gate rating curve with forebay WSE measured at the upstream end of the fish screen.

Sediment Test Results

South Fork Battle Creek is a high gradient mountainous stream, and as a result, large volumes of sediment are expected with high flow events and sedimentation has been a concern in other hydropower supply canals owned by PG&E in the Battle Creek watershed. For this reason, there is an existing sediment basin in the Inskip diversion which is planned to be modified with the construction of this new facility. Two tests were performed to assess the functionality of the sediment basin: 1.) to determine the effectiveness of the sluice gate at removing sediment deposits and 2.) to determine how well sediment that enters the diversion is captured by the sediment basin, and how much is transported downstream along the fish screen.

Sediment gradations used for the 1:5 scale model can be found in Figure 36 which contains gradations for samples collected from the Coleman Canal, as well as Battle Creek surface and subsurface samples collected in 2001 at the Inskip Diversion Dam site. The concrete sand gradation used in the physical model matches well, but does not contain the very coarse or the very fine fractions of the Coleman samples.

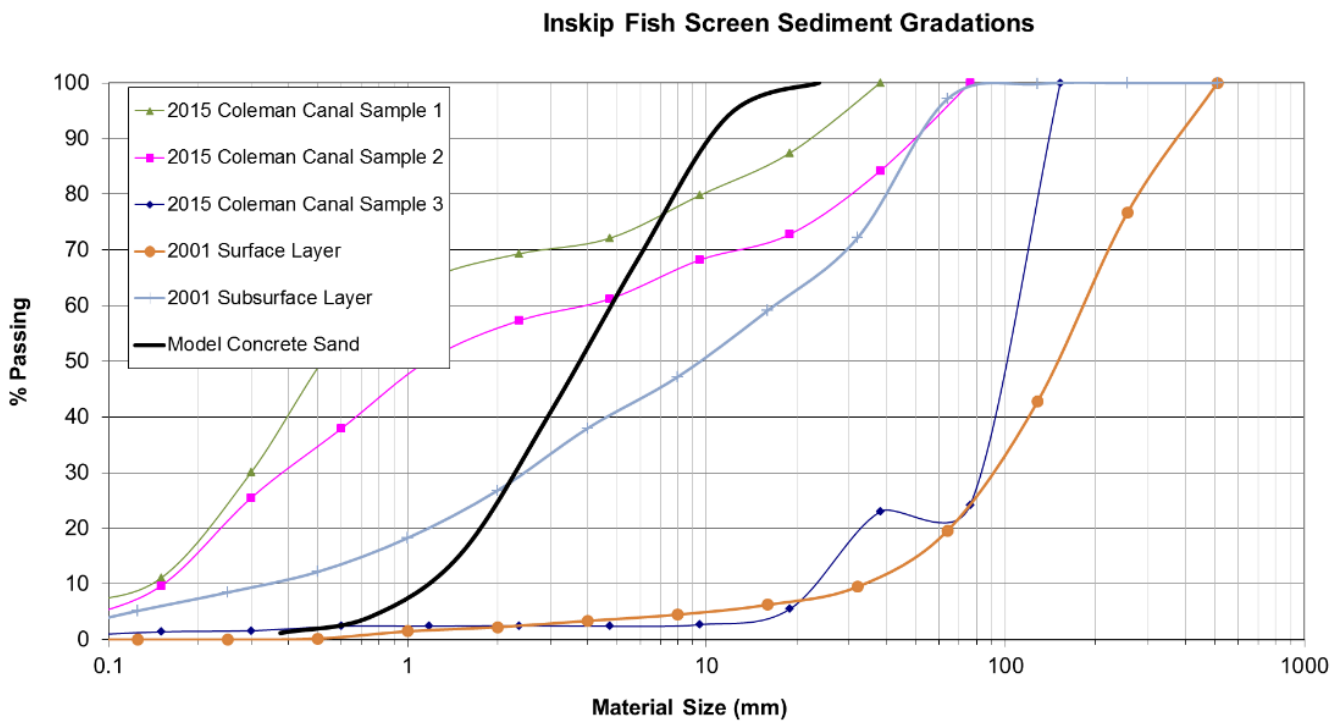


Figure 36. Sediment gradations for 1:5 scale model.

Initial tests for the sediment basin sluice gate efficiency started by allowing flow to pass over the sediment basin when it was filled to elevation 1432 feet (matches the diversion channel invert elevation both upstream and downstream of the basin). Two different flow rates and flow distributions were allowed to run until sediment transport ceased with the sluice gate closed for the duration of the test. These tests were run to determine the sediment levels that would be reached after an extended period of operation. The first test that was run was a total diversion flow of 242 cfs, with 55 cfs for the canal, 148 cfs through the AWS and 39 cfs for the fish ladder. The second test was a total diversion of 259 cfs, with 220 cfs for the canal, 0 cfs through the AWS and 39 cfs for the fish ladder. Results for both tests indicate that very little erosion of sediment is likely once the sediment basin has become filled. Additional sediment that might enter the diversion intake was not tested, but would be expected to pass the sediment basin.

Following the full sediment basin tests, the sediment basin sluice gate was opened to fixed gate openings and sediment transport was allowed to stabilize with the maximum diversion flow of 259 cfs. Once sediment was no longer observed being eroded from the sediment basin, the gate was closed and model flows were halted to measure sediment basin depths. Three partial sluice gate openings were tested (1.0 foot, 2.0 foot and 4.0 foot) as well as the gate opened until free flow was established. During the sluicing tests, flow passing down the fish ladder was adjusted to maintain 39 cfs, if possible. When flows dropped below 39 cfs, the swing gate was fully opened and the flow passing down the ladder was measured.

The prototype time to reach transport equilibrium are listed on Figure 37 through Figure 40. These figures show the progression of sediment basin erosion contours for various gate openings. During testing, the decision was made to skip modeling a sluice gate opening of 3 feet due to the minimal change in erosion between the 1.0 foot and 2.0 foot openings. However, it appears that there is a large increase in the erosion rates when the sluice gate is opened greater than 2 feet. There is potential that a large amount of sediment may be able to be cleared from the sediment basin when the sluice gate is

opened between 2.0 and 4.0 ft while the facility is still able to provide a small amount of flow to the fish ladder. This may prevent fish in the ladder from becoming stranded in the ladder pools.

With the erosion of the sand from the sediment basin, small dunes were observed forming in the fish screen forebay, and a small amount of sediment passed through the fish screen and settled out behind the screens. No sediment was deposited in the fish ladder. The dunes that had deposited in the screen forebay were small, and were likely limited in development by the fact that a majority of the scoured sediment was exiting the system through the sediment basin sluice gate.

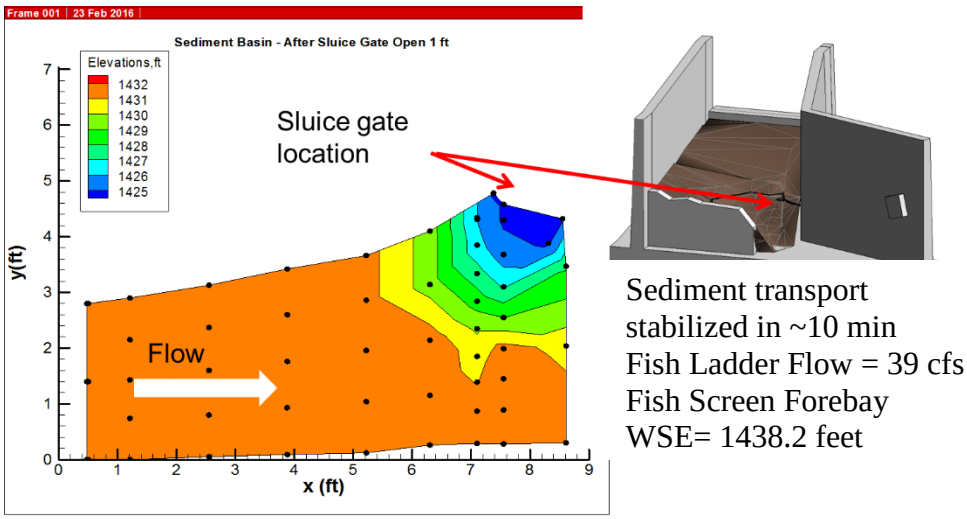


Figure 37. Sediment basin erosion contours after the 1.0 foot sluice gate opening test. The black dots are locations where sediment depth measurements were collected.

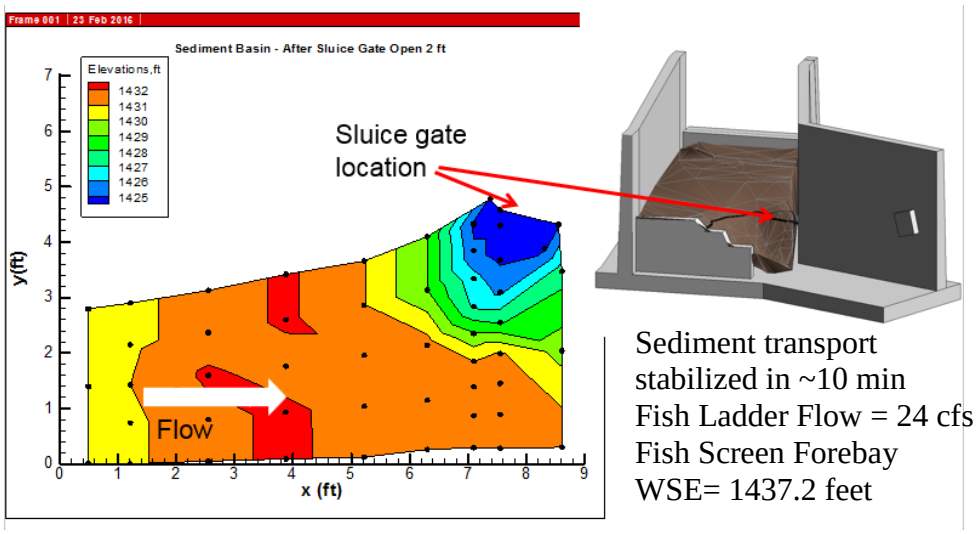
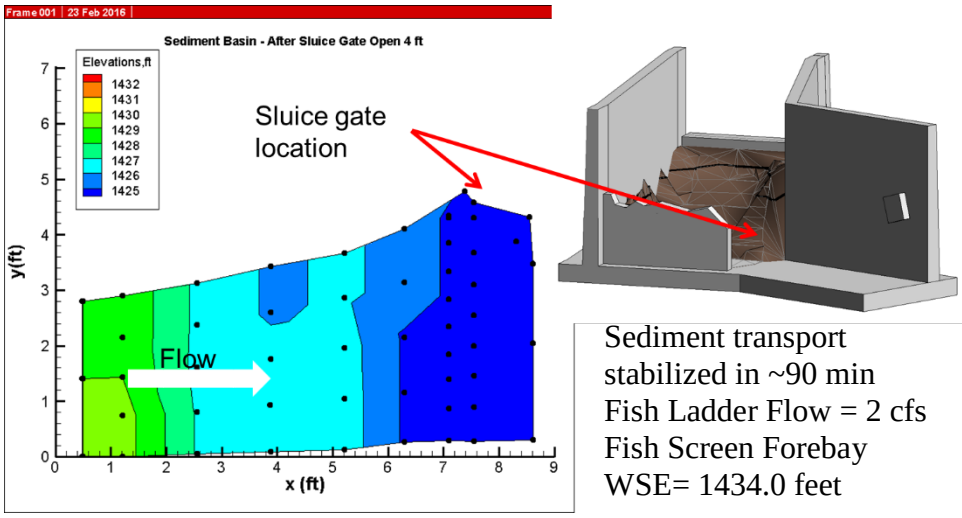
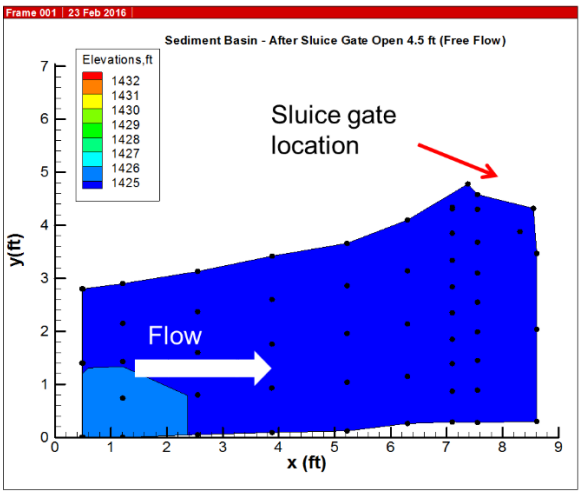


Figure 38. Sediment basin erosion contours after the 2.0 foot sluice gate opening test.



Sediment transport stabilized in ~90 min
Fish Ladder Flow = 2 cfs
Fish Screen Forebay WSE= 1434.0 feet

Figure 39. Sediment basin erosion contours following the 4.0 foot sluice gate opening test.



Remaining sediment cleared rapidly
Fish Ladder Flow = None
Fish Screen Forebay WSE= Dry

Figure 40. Sediment basin erosion contours following the test with the sluice gate fully opened.

To test the effectiveness of the sediment basin's ability to capture sediment transported by flow through the diversion, concrete sand was added to flow in the diversion canal just downstream from the headworks gate. Initially, about 60 cubic yards (prototype) of concrete sand was gradually added to the canal with a total diversion flow of 259 cfs. Model flow was held constant without additional sediment being introduced for approximately 30 hours (prototype). After 30 hours, a sand dune had formed in the diversion canal, but only a very small amount passed into the sediment basin. Dunes were observed in the fish screen forebay, and were approximately 3 inches high (prototype). Slight amounts of sediment passed through the fish screen, but no sediment deposited in the fish ladder pools. Figure 41 and Figure 42 illustrate the amount of sediment deposition observed following the first part of this test.

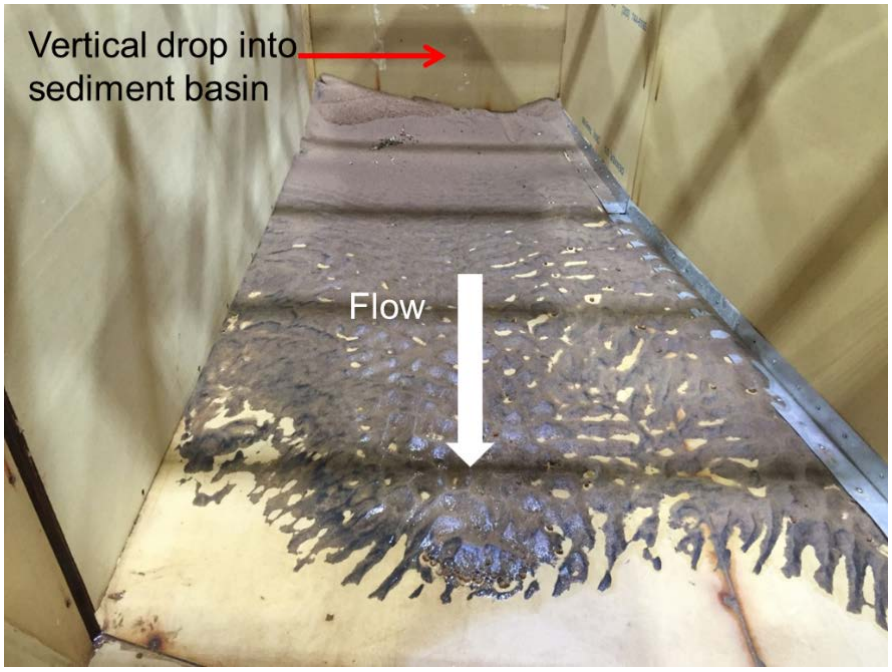


Figure 41. Sediment basin sediment deposition 30 hours after 60 cubic yards of concrete sand was added to the diversion canal (looking upstream). Notice the larger area of deposition just after the vertical drop.

Figure 42. Fish screen forebay sediment deposition 30 hours after 60 cubic yards of concrete sand was added to the diversion canal (looking downstream).

The sediment deposition and transport test was continued the following day by adding an additional 60 cubic yards (prototype) of concrete sand rapidly and allowing the flows to continue for an additional 20 hours (prototype). At this point, the diversion canal was filled to a uniform depth of about 16-20 inches (prototype) and the sediment in the diversion canal had migrated to the entrance of the sediment basin. Once the sediment reached the intermediate gate, transport was rapid due to the flow acceleration around the gate structure. Sediment transported past the intermediate gate deposited just downstream from the vertical drop into the sediment basin as shown in Figure 43. The continued sediment addition resulted in a minor amount of sediment downstream of the sediment basin, with a slightly altered deposition pattern. A slightly greater amount of sediment passed through the fish screen as shown in Figure 44

which was taken just upstream of the tilt gate. A relative comparison of the sediment sizes at each location can be found below in Figure 45.

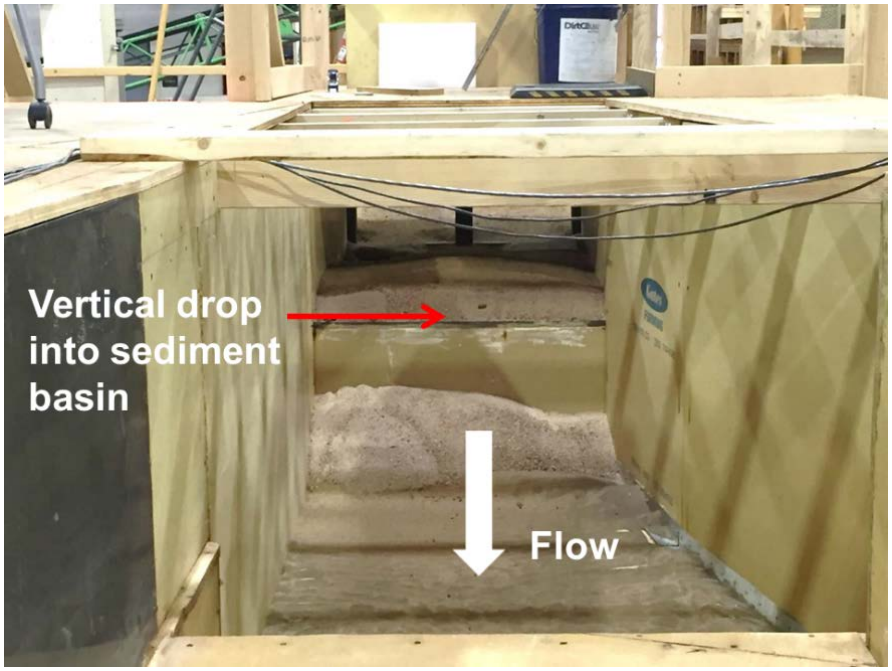


Figure 43. Sediment basin deposition 50 hours after 120 cubic yards of concrete sand was added to the diversion canal (looking upstream).

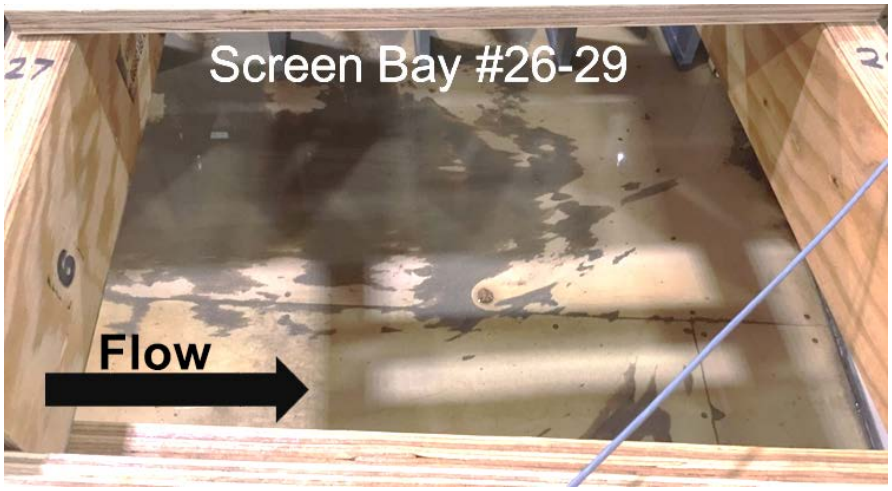


Figure 44. Sediment deposited behind the fish screen near the tilt gate structure.

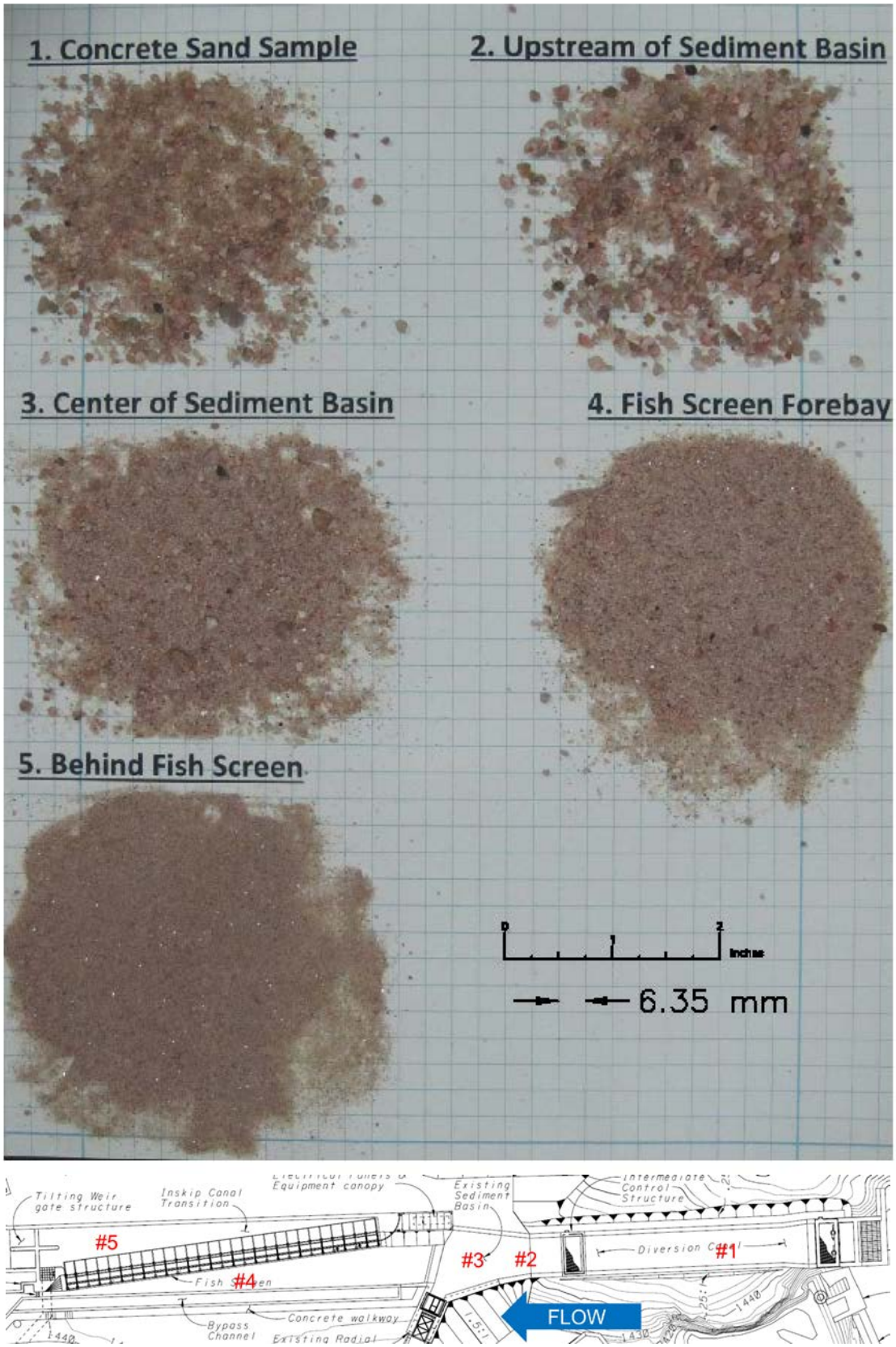


Figure 45. Deposited sediment by location.

Flow Measurement with the Tilt Gate

A head-discharge relationship for the tilt gate was attempted to be created with the physical model however the hydraulic conditions were unreliable due to operation of the AWS. The proximity of the AWS intake to the tilt gates created considerably different approach conditions when the AWS was being operated. Since the AWS is likely to be operated frequently, flow measurement using the tilt gates is not recommended for the new facility. A flow measurement station in the canal downstream from the tilt gate structure is recommended. Figure 46 shows the flow conditions over the tilt gate during Test 14. While the WSE is stable on the right gate (looking downstream at the gate structure), the water surface is very turbulent leading to an unstable nappe on the left gate. The turbulence is caused by the design of the AWS inlet and its location relative to the pier which isolated flow between the two gates approach channels.

Figure 46. Photograph of flow conditions over tilt gates taken during Test 14 showing different approach conditions between left and right tilt gates (looking upstream).

1:8 Scale Fish Ladder Entrance Chamber and Diversion Dam Model

Fish Ladder Entrance Chamber Gate Results

Having multiple gates on the fish ladder entrance chamber allows a wide variety of options on how the entrance chamber is operated. While this is a benefit to fisheries and provides flexibility in operation, it also adds complexity to the facility and a decision-level analysis of gate priority. In all tests performed with the hydraulic model, the fish ladder entrance chamber gates were operated to achieve a 1.0 foot head differential between the WSE inside the entrance chamber and the river water surface elevation whilst keeping Gate D fully open during all tests. Laboratory tests confirmed that the designed gates have sufficient capacity to meet fish ladder flow demands for all flows up to 1870 cfs. The blue dots in Figure 47 shows the cumulative open area (in square feet) of the gates required to create a 1.0 foot WSE differential. The solid black line is the maximum gate area available if all gates were open.

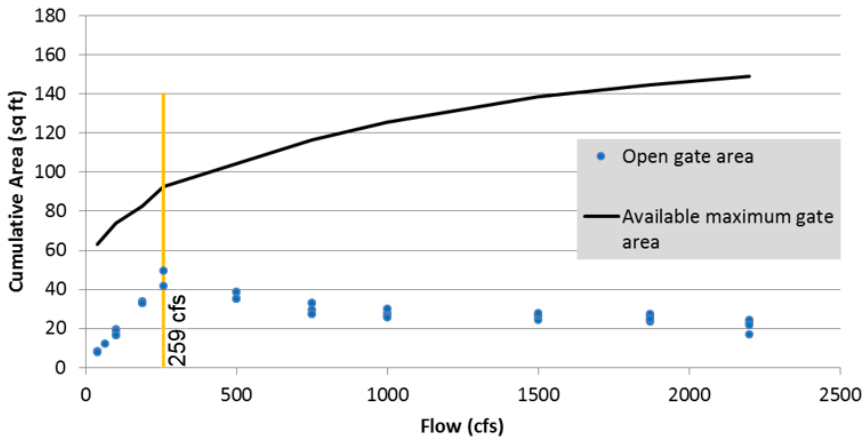


Figure 47. Fish ladder entrance chamber gate open area required to achieve 1.0 ft drop in WSE between the inside of the fish ladder entrance chamber and the river (blue dots). The total available gate area for each flow, based on the WSE is represented by the solid black line. For flows less than 259 cfs, all water passes through the fish ladder. For flows greater than 259 cfs, water passes through the fish ladder and over the dam.

In Figure 47, the blue dots show the spread in the open area required to meet the 1.0 foot water surface differential and shows the range in open area dependent on which combination of gates is being used. Tests found that some combinations of gates were more efficient at allowing water in the entrance chamber to pass to the river channel (and therefore required a smaller open area). As can be seen in Figure 48, flows coming over Inskip Diversion Dam along the left bank of the channel approach the fish ladder entrance chamber in almost the opposite direction as flows passing through the gates. This results in reduced efficiency of certain gates which requires a larger gate opening to maintain the desired WSE inside the chamber. The converse is true for gates further downstream (Gates C and B) where the river flow vector is parallel to the entrance chamber wall, and therefore makes the gates more efficient at passing flow.

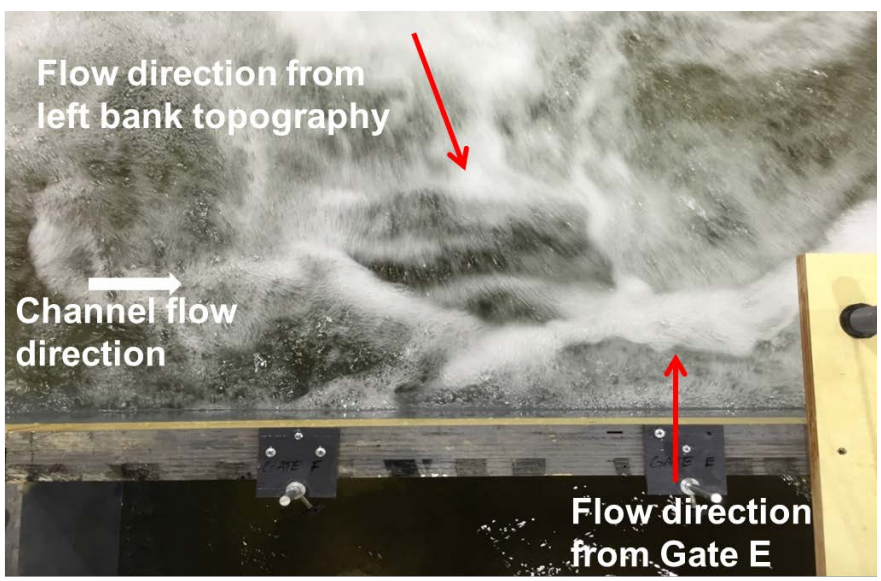


Figure 48. Fish ladder exit chamber flows from Gate E at 187 cfs exiting the chamber, and 1683 cfs in the river for a total flow of 1870 cfs.

Rating Curve Results

A rating curve for the fish ladder entrance chamber and the river just outside of the entrance chamber was measured in the physical model. By adjusting where the entrance chamber flows entered the river, the rating curve for the river resulted in a range of potential water surface elevations depending on operations. Similarly, since the fish ladder entrance chamber WSE is set to create a 1.0 foot differential with the river WSE, the fish ladder entrance chamber WSE was also impacted. In the physical model, water surface elevations were measured roughly half the distance between Gate E and Gate D. Table 3 and Figure 49 show the rating curve data for the fish ladder entrance chamber and the river WSE directly adjacent to the fish ladder entrance chamber. The rating curve for the water surface elevation above the dam can be found in Table 4 and Figure 50 respectively.

Table 3. Rating curve for fish ladder entrance chamber and river directly outside of the fish ladder entrance chamber. For flows less than 259 cfs, all flow is assumed to pass through the Inskip canal diversion and reach the river by combination of AWS and fish ladder. For flows greater than 259 cfs, water passes through the fish ladder and over the dam. The range of elevations is due to the various combinations of fish ladder entrance gates being used.

Flow (cfs)	Fish Ladder High Bound (Elev, ft)	Fish Ladder Low Bound (Elev, ft)	Channel High Bound (Elev, ft)	Channel Low Bound (Elev, ft)
39	1412.15		1411.2	
100	1412.77	1412.76	1411.82	1411.82
187	1413.59	1413.58	1412.67	1412.65
500	1415.38	1415.24	1414.37	1414.22
750	1416.56	1416.23	1415.55	1415.16
1000	1417.46	1417.09	1416.51	1416.10
1500	1419.03	1418.44	1418.07	1417.47
1870	1420.1	1419.34	1419.15	1418.39

Figure 49. Rating curve for fish ladder entrance chamber and river directly outside of the fish ladder entrance chamber.

Table 4. Rating curve for Inskip Diversion Dam with WSE measured upstream of the dam.

Flow (cfs)	Upstream WSE (ft)
0	1439.00
250	1440.02
500	1440.64
750	1441.16
1000	1441.60
1500	1442.30
2000	1442.85
2500	1443.43

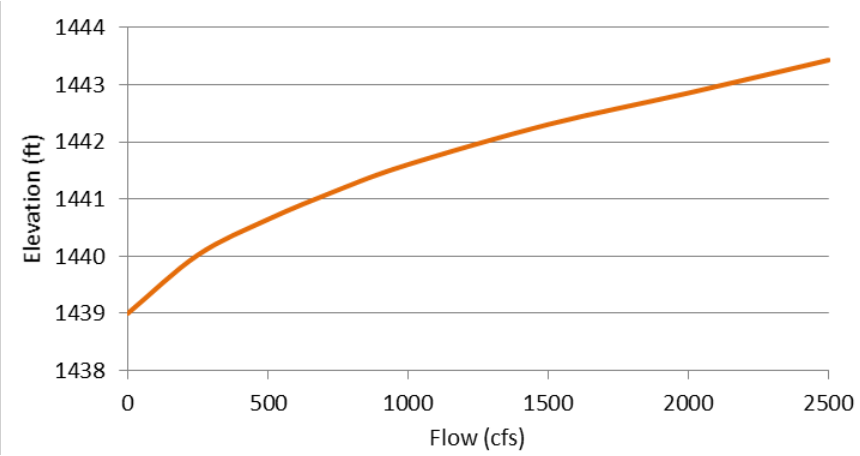


Figure 50. Rating curve for water surfaces upstream of Inskip Diversion Dam.

Auxiliary Water System Test Results

The vertical velocity component of the AWS diffuser was tested to ensure it is less than 1.0 ft/s to meet the NMFS criteria. Velocities were recorded adjacent to the diffuser grating along the centerline of the floor diffuser located in the entrance chamber. From upstream to downstream, the test locations were set at the axis of each gate, and half the distance between gates as shown in Figure 51. All velocities were tested with a flow rate of 187 cfs through the fish ladder entrance chamber (148 cfs through the AWS and 39 cfs down the fish ladder) and no flow coming over Inskip Diversion Dam which gives a reasonable maximum velocity of the floor diffuser. For all configurations, Gate D and one other gate were fully opened, and an additional gate was partially opened to meet the 1.0 foot WSE differential. Gate B was not utilized for these tests since only 1.5 foot (prototype) of water was above the invert which would have required a 4th gate to be opening to maintain 1.0 foot WSE differential between the entrance chamber and the river.

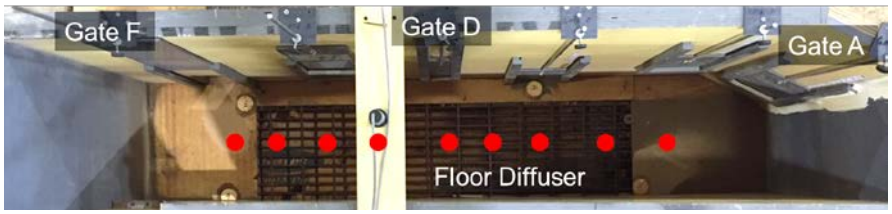


Figure 51. Diffuser screen vertical velocity sampling locations.

Vertical velocities from the floor diffuser were also affected by the gate operation of the fish ladder entrance chamber. As can be seen below in Table 5, all operational conditions met the 1.0 ft/s maximum vertical velocity when all measurements were averaged. Figure 52 shows how the velocities varied along the sampling locations. Almost all operations had their lowest vertical velocity located between gates B and C, which could be a potential location for an additional baffle for the floor diffuser. However, since the average velocity criteria was met for all operations, no additional baffling was investigated.

Table 5. Diffuser grating average velocities. The first two gates listed were fully open and the third gate listed was partially opened as indicated by the percent value in parentheses.

Gate Operation	Average Vertical Velocity (ft/s)
Gate D, F and A (40%)	**0.40**
Gate D, F and C (40%)	**0.38**
Gate D, F and E (40%)	**0.36**
Gate C, D and A (40%)	**0.52**
Gate C, D and E (40%)	**0.52**
Gate C, D and F (40%)	**0.56**

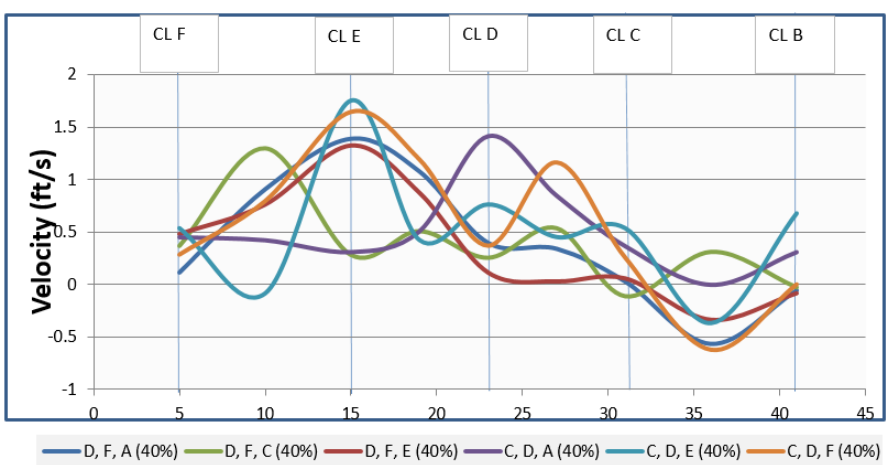


Figure 52. AWS diffuser grating vertical velocities. Gate centerline (CL) locations are marked at the top of the plot.

Sediment Test Results

Tests to qualitatively analyze sediment were also investigated with the 1:8 scale diversion dam and fish ladder entrance chamber model. Figure 53 contains the sediment gradations for samples near the Inskip Diversion Dam, and compares the scaled sizes of materials that were tested in the lab. As can be seen in the plot, the concrete sand matches the D50 closely with the subsurface layer, but the model sand is more uniformly graded than the subsurface sample. The surface sample is more coarse than the model pea gravel, but not as coarse at the 1.5-inch rock. The finest fraction of potential samples is missed from the model material samples, however if the flow is able to scour the coarser particles, it should be able to mobilize the finer grain sizes. Therefore, tests were designed to look at worst case occurrences of areas that could potentially fill with sediment during a major flood event and can be found below in Table 6. For any test that included flow over the dam, the dam sluice gate was operated to test whether the sluice gate aided in eroding sediment deposited in the excavated entrance pool.

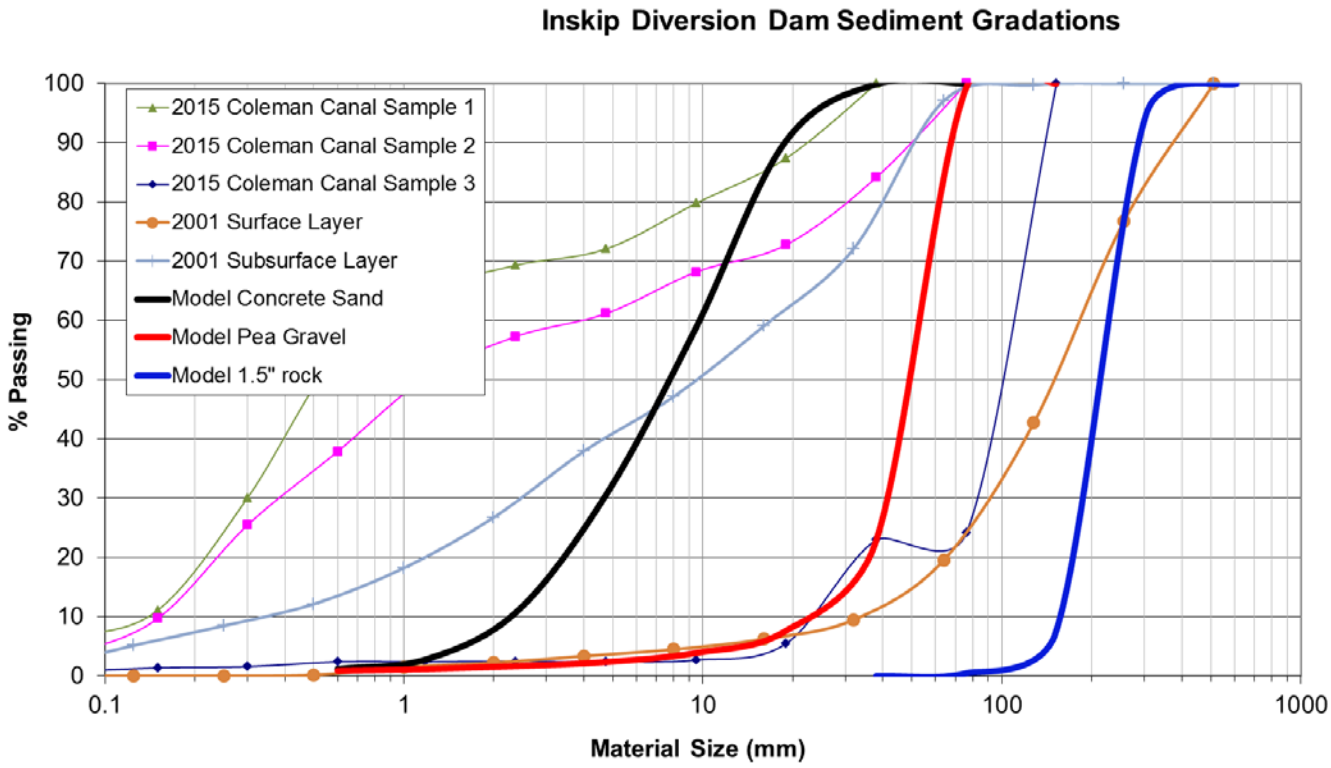


Figure 53. Sediment gradations for the 1:8 scale model.

Table 6. Test matrix for 1:8 scale model sediment tests.

Test Number	Total Flow (cfs)	Fish Ladder Flow (cfs)	Auxiliary Flow (cfs)	Flow over the Dam (cfs)	Notes
Test 4	39	39	0	0	Add concrete sand to fish ladder during flow
Test 5	39	39	0	0	Fill diffuser sump with sand, test ability to scour
Test 6	100	39	61	0	Continue Test 5 with higher flows
Test 7	187	39	148	0	Continue Test 5 with higher flows
Test 8	259	39	220	0	Continue Test 5 with higher flows
Test 9	187	39	148	0	Fill excavated pool to 2' prototype with concrete sand.
Test 9b	500	39	148	313	Continue Test 9 with higher flows
Test 10	187	39	148	0	Fill excavated pool to 2' prototype with pea gravel.
Test 11	500	39	148	313	Continue Test 10 with higher flows
Test 12	750	39	148	563	Continue Test 10 with higher flows
Test 13	1000	39	148	813	Continue Test 10 with higher flows
Test 14	1500	39	148	1313	Continue Test 10 with higher flows
Test 15	1870	39	148	1683	Continue Test 10 with higher flows
Test 16	1870	39	148	1683	Added 1.5" rock to model at dam
Test 17	2200	39	148	2013	Continue Test 15 with higher flows
Test 18	1870	39	148	1683	Excavated entrance pool filled to 2’ with matrix of sand, pea gravel and 1.5” rock.

Test 4 was designed to analyze how fine sediment traveling down the fish ladder would behave when entering the backwater created by the fish ladder entrance chamber and was tested both with the concrete sand as well as sand recovered from the fish screen forebay of the 1:5 scale model. Once flows were established to the model, approximately 7 cubic feet (prototype) of sand was gradually added to the pool above weir 22 and was allowed to reach equilibrium. During the test, different operations of the fish ladder entrance chamber gates were investigated to determine if gate configuration impacted deposition patterns. In order to document the best scenario, gates were opened in a sequence from least likely to erode sediment to more likely to erode sediment while maintaining a 1.0 foot WSE differential between the fish ladder entrance chamber and the river.

The sand from the 1:5 scale model is considerably finer than the concrete sand material (see Figure 45), but prototype material passing through the fish ladder would be roughly 63% of the diameter of the sand from the 1:5 scale model due the scale differences of the 1:5 and 1:8 scale model. Based on the result of the 1:5 scale model, very little sand should deposit in the ladder pools, with only a small amount being deposited due to backwater at the downstream end of the ladder as illustrated by this test.

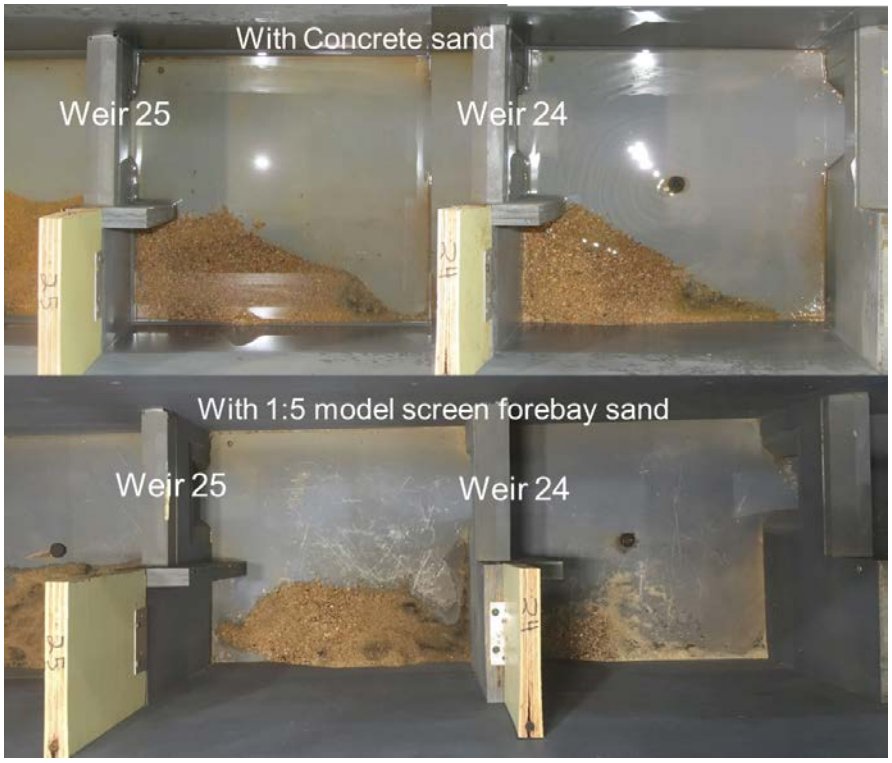


Figure 54. Comparison of fish ladder sedimentation with concrete sand and 1:5 fish screen forebay sand.

Tests 5-8 were designed to evaluate the ability of the AWS diffuser to clear any deposited sediment beneath the diffuser screen. This was accomplished by filling the area below the screen with concrete sand and allowing flows to erode any material. Flows progressed from only using the 39 cfs from the fish ladder (and no flows from the AWS) to a maximum of 220 cfs from the AWS in addition to 39 cfs from the fish ladder. In addition to increasing flows from the AWS, each individual flow rate utilized a progression of gate operations to determine the impacts of gate settings on the erosion potential. Results indicate that erosion of sediment deposited beneath the floor diffuser was very dependent on flow through the AWS, and less dependent on gate operations.

Figure 55 contains a series of photographs of the location of sediment clearing as the total flow (combination of 39 cfs down the fish ladder with the remaining from the AWS flow) increases. As can be seen, the ability to clear the material is possible at partial AWS flows, but is greatly increased as AWS flow is increased. At 187 cfs, which is the expected typical operation with 39 cfs coming down the fish ladder and 148 cfs through the AWS, sand deposited at the shallow edge of the diffuser chamber floor was not able to be transported. The prototype's ability to scour sand from the AWS diffuser will likely be improved from the physical model results since the sand used for this test was coarser than what would be expected to pass the fish screen and travel down the fish ladder.

At the maximum possible diversion of 259 cfs, which includes 39 cfs coming down the fish ladder and 220 cfs through the AWS, only a very small amount of sand remained at the shallow end of the AWS diffuser chamber. Gate operations appeared not to have a major impact on ability to clear the diffuser chamber as long as gates with lower inverts were used (Gates C and E were utilized in the tests, but the modified Gate F would work similarly if not better than Gate E due to a lower invert elevation).

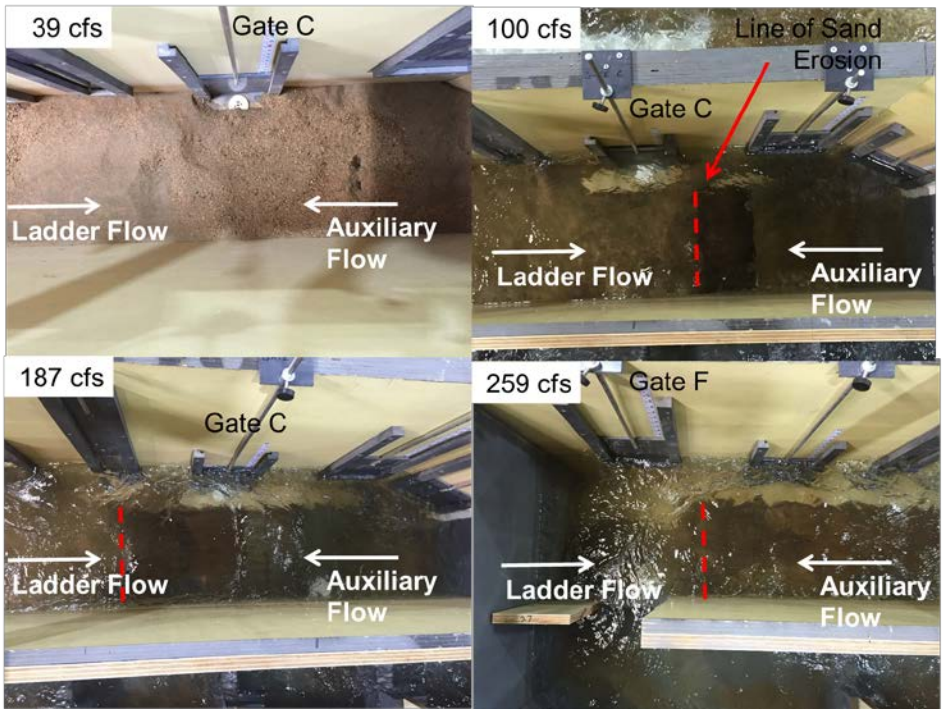


Figure 55. Comparison of AWS ability to erode sediment deposited beneath the AWS diffuser.

Tests 9 through 16 investigated the ability of flows through the fish ladder entrance chamber and over the dam to erode any material that becomes deposited in the excavated entrance pool. Material was placed dry to an approximate depth of 2 foot (prototype) with material that varied from all concrete sand, all pea gravel and a matrix of sand, pea gravel and 1.5-inch rock. Flow rates were started at low values, and gate operations were adjusted from least likely to erode material to more likely before increasing flow rates and gate operations. At 187 cfs (all flow coming from the fish ladder entrance chamber), gates with lower invert elevations easily mobilized sediment from a region near the gate. With concrete sand in the excavated entrance pool, even Gates D and E with an invert elevation 3.5 feet and 2 feet (prototype), respectively, above the excavation elevation were able to mobilize material. At this flow rate, some sand particles were seen exiting the excavated entrance pool and being transported down the river channel. Initially, a sediment ramp would build in the downstream corner of the excavated entrance pool to the river channel elevation, and sediment transport would occur up the ramp and out into the channel as shown in Figure 56.

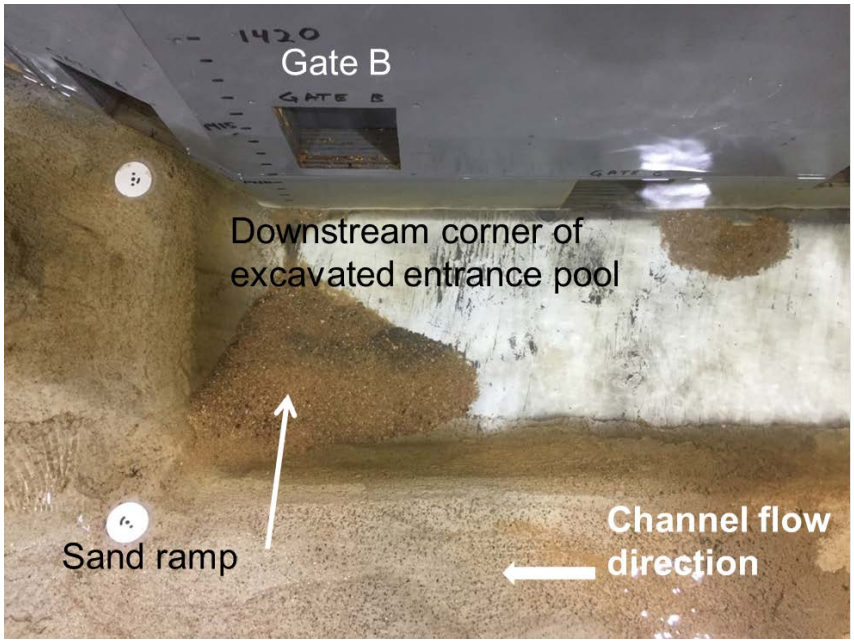


Figure 56. Sand Ramp Formation at downstream end of excavated entrance pool following Test 9b with 500 cfs.

Following Test 9 at 187 cfs, flows over the dam were introduced to give a total flow rate of 500 cfs with 187 cfs through the fish ladder entrance chamber and 313 cfs over the dam (Test 9b). With the higher flows, an area between Gate E and the downstream sand ramp was completely cleared of sediment as shown in Figure 56. The upstream area that was not cleared of sand remained since the invert elevation of the originally designed Gate F was too high to mobilize any of the deposited material. When the dam sluice gate was operated, more sand was cleared from the excavated entrance pool than with just flows over the dam crest.

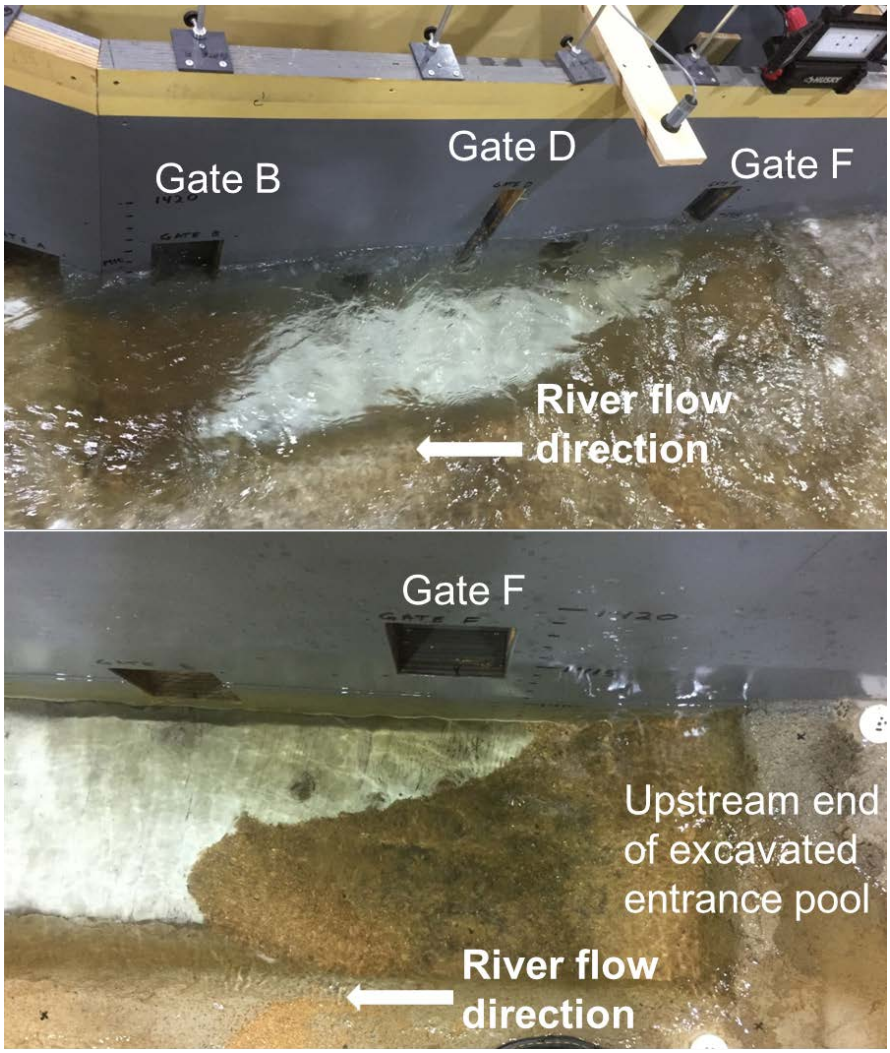


Figure 57. Sand erosion following 500 cfs (Test 9) with the dam sluice gate open.

Following the test with concrete sand deposited in the excavated entrance pool, pea gravel was used. In the upstream area where sand remained, pea gravel was placed on top of the sand and was embedded to attain a total fill depth of 2.0 feet (prototype). Flows were started at 187 cfs through the fish ladder entrance chamber before adding flows over the dam and gate operations were sequenced from least like to erode to more like to erode material. At 187 cfs, pea gravel deposited in front of Gate C was able to be mobilized within seconds of the gate being opened and cleared a semicircle with about a 4 foot (prototype) radius around the gate as shown in Figure 58.

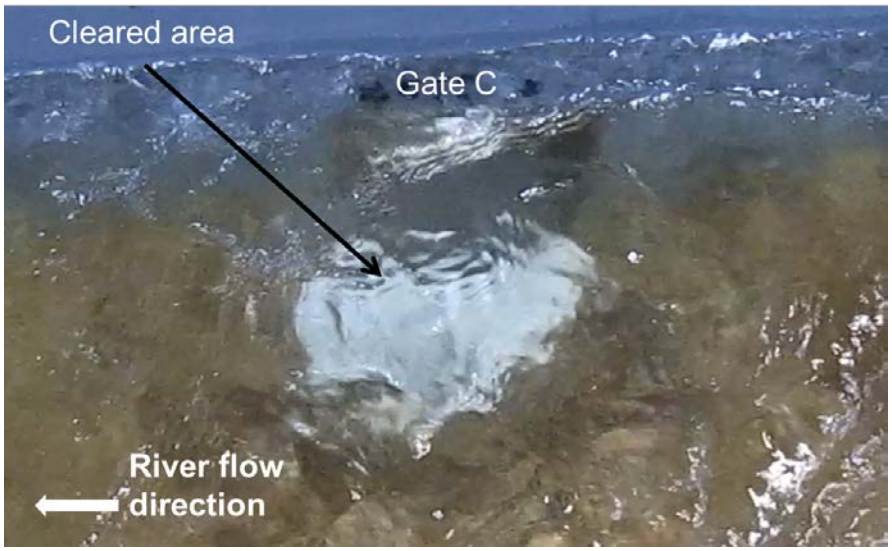


Figure 58. Ability of Gate C to clear pea gravel at 187 cfs (Test 10).

After increasing total river flow to 500 cfs by adding 313 cfs over the dam (Test 11), a downstream sediment ramp formed similar to the concrete sand tests as shown in Figure 59. Gates with lower invert elevations performed better at mobilizing the pea gravel within the excavated entrance pool. However, unlike the sand tests, Gates D and E were not able to mobilize the pea gravel without the aid of the dam sluice gate being opened. Operation of the dam sluice gate aided in transporting pea gravel towards the downstream sediment ramp and out of the excavated entrance pool. Sediment deposited upstream of Gate E was unaffected by flows over the dam either with or without the dam sluice gate being opened.

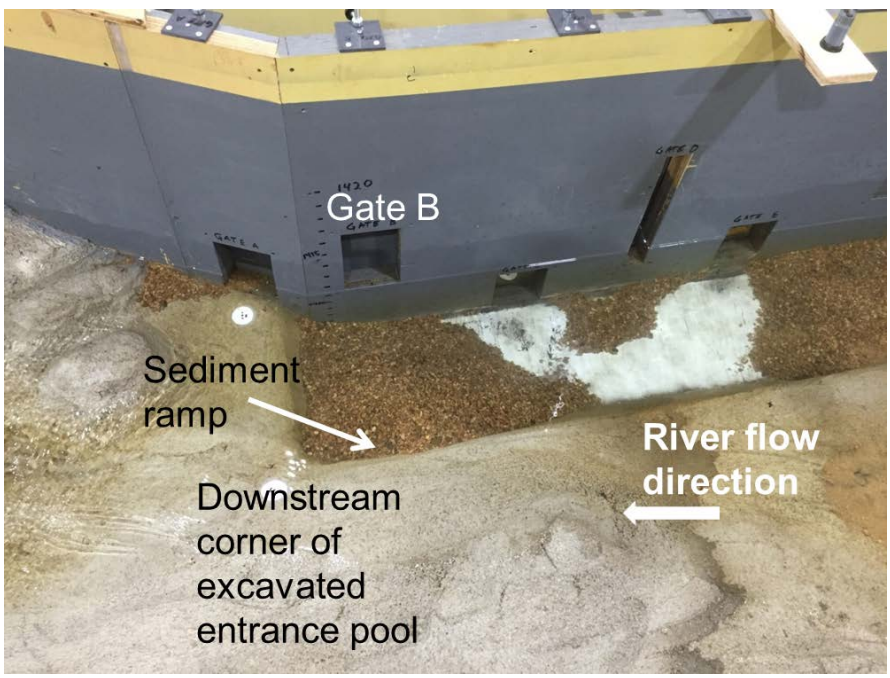


Figure 59. Excavated entrance pool following 500 cfs with sluice gate open (Test 11).

As flows were increased to 750, 1000 and 1500 cfs, almost all pea gravel downstream of Gate E was scoured from the excavated entrance pool with the exception of a small portion of the downstream

sediment ramp that remained at 750 cfs, but was fully eroded at 1500 cfs as shown below in Figure 60. When flows were increased to 1870 cfs, the remaining pea gravel in the upstream end of the excavated entrance pool was able to mobilize partially with the Inskip dam sluice gate closed, and was completely removed when the sluice gate was opened.

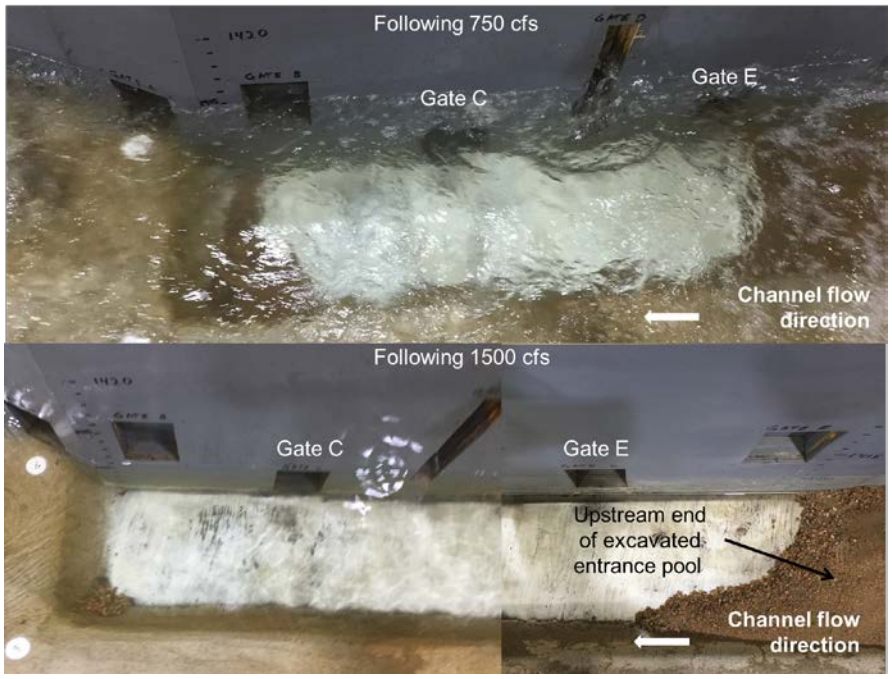


Figure 60. Excavated entrance pool following 750 and 1500 cfs (Tests 12 and 14).

Conservative tests to determine how well the largest grain size recorded in South Fork Battle Creek would be mobilized included using 1.5-inch rock in the physical model which scales to 12-inch boulders in the prototype and can be found on the surface layer. Rocks this large may enter the excavated entrance pool either as colluvium from the hillslopes, or as the dam sluice gate is opened during sediment clearing operations. Material was added to the model in three locations, over the dam crest, in front of the sluice gate and between the sluice gate and the upstream edge of the excavated entrance pool.

Rock that was loaded into the channel from the left side of the dam was transported rapidly downstream and generally did not enter the excavated entrance pool. Material transported through the sluice gate was able to move slightly downstream, but slower velocities between the sluice gate and the excavated entrance pool allowed the rock to deposit with only a small portion entering the excavated entrance pool. Similarly, when material was loaded immediately upstream of the excavated entrance pool, much of the rock remained where it was placed, while some of it was mobilized into the excavated entrance pool as shown in Figure 61. When material entered the excavated entrance pool, it would primarily remain in the area upstream of Gate E, or be transported out of the excavated entrance pool.

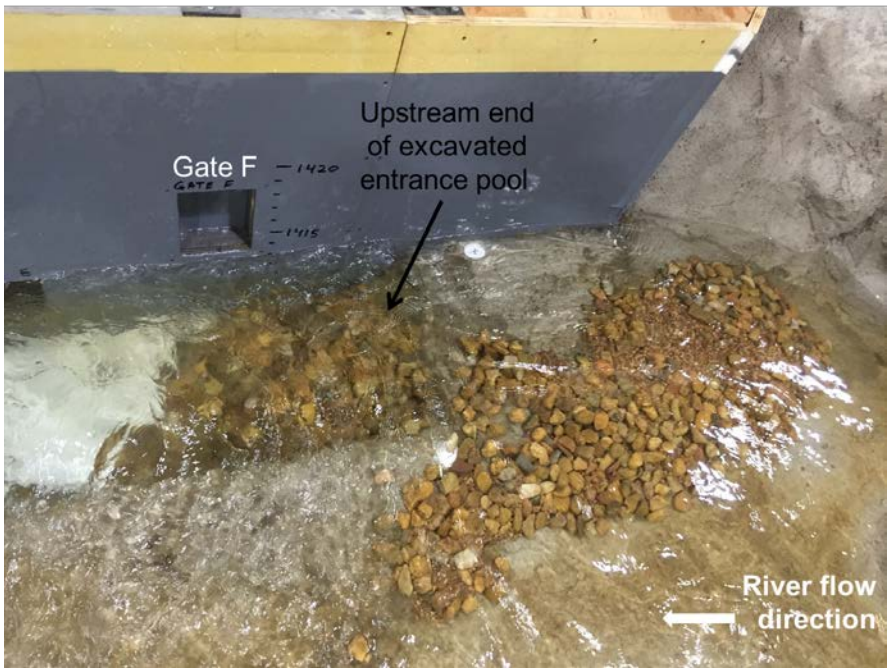


Figure 61. Following 1870 cfs 1.5 inch rock test with sluice gate open (Test 16).

Test 18 was performed by filling the excavated entrance pool with a matrix of sand, pea gravel and 1.5-inch rock to a depth of 2.0 foot (prototype). By slowly increasing flows up the design flow, erosive ability of transitional flow rates were observed. With only 187 cfs coming from the fish ladder entrance chamber, Gate C was again able to mobilize sediment in front of the gate. With a flow rate of 1870 cfs (with 187 cfs from the fish ladder entrance chamber and 1683 cfs over the dam) Gates C, D and E were able to clear a portion of the rock from the excavated entrance pool even without the dam sluice gate being opened as illustrated by Figure 62. By opening the sluice gate, the rock deposited in the upstream of the excavated entrance pool was relatively unchanged, but the amount of rock along the far side of the pool and the downstream ramp were decreased.

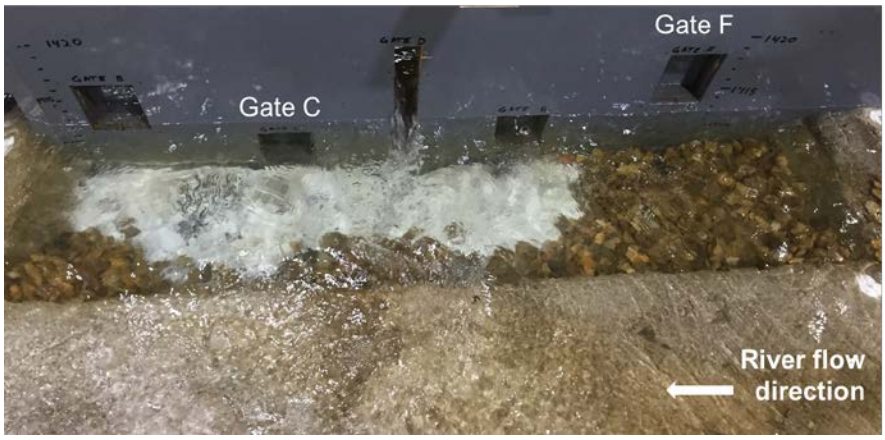


Figure 62. Matrix of sand, pea gravel and 1.5-inch rock following 1870 cfs without dam sluice gate operation (Test 18).

Operation of the Inskip dam sluice gate appeared to provide additional scour potential for the downstream portion of the excavated entrance pool. With the original fish ladder entrance chamber

design, sediment remained in the area upstream of gate E even with the sluice gate operation. The modified fish ladder entrance chamber design (relocation of Gates E and F), and altered excavation will aid in the ability of all flows (either with or without sluice gate operation) to mobilize sediment from the excavated entrance pool, but were not tested due to the acceptable performance of the original design in ability to clear deposited sediment.

Inskip Dam Sluice Gate Ability to Pass Sediment

Upstream of the Inskip dam sluice gate, a matrix of both pea gravel and 1.5” rock where used to determine the ability of the sluice gate to evacuate deposited material upstream of the gate. With a sluice gate opening of 10 feet (prototype) and a flow of 1683 cfs upstream of the dam, the sluice gate was able to erode sediment from an area approximately 12 feet upstream with a slight increase in distance along the face of the dam as shown below in Figure 63. From the Headworks Modification drawing 0A-60-204, it appears there is a minimum distance of approximately 18 feet between the sluice gate and the canal headworks base of the trash rack and a 4 foot vertical drop. It is unlikely that the dam sluice gate will effectively clear the area in front of the canal headworks.

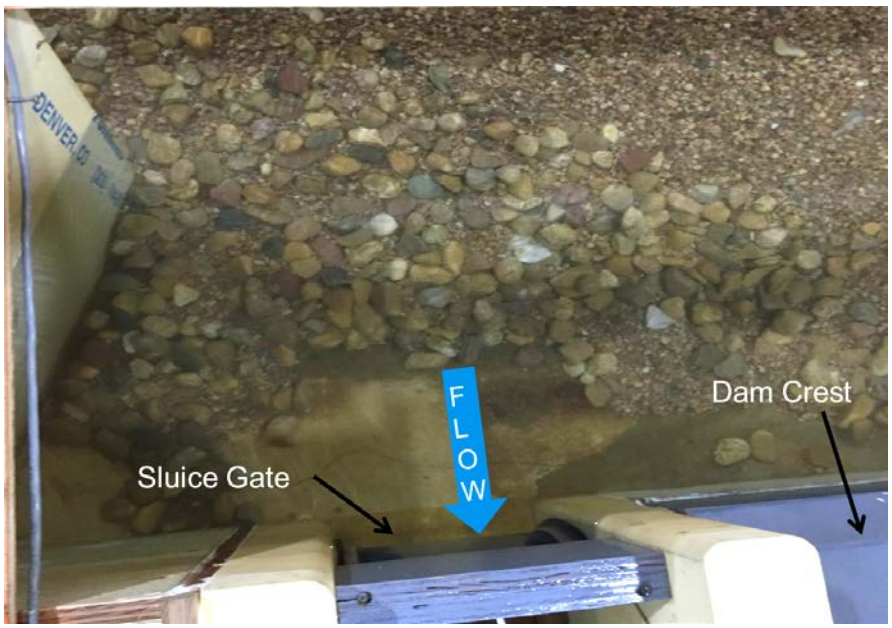


Figure 63. Sediment remaining upstream of the Inskip Dam sluice gate after a flow of 1683 cfs with a sluice gate opening of 10 feet.

Sediment Tests Following Fish Ladder Entrance Chamber Modifications

Selected sediment tests were repeated following the modifications to the excavated entrance pool and gates of the fish ladder entrance chamber. Modifications included lowering the invert elevation of Gate F, raising Gate E (to match the original design invert of Gate F), altering the upstream and downstream slope of the excavated entrance pool and narrowing the lateral extent of the excavated entrance pool excavation.

One test that was replicated was introducing the 1:5 scale model forebay sand down the fish ladder. Comparison photographs showing the ability to pass sand before and after the modification can be found in Figure 64 at only 39 cfs. With the original design, only a small portion of the finer sand passed through Gate C, D or E because they either had a higher invert elevation or they were further away from

the fish ladder. The modified design is much more efficient at passing sediment that comes down the fish ladder since flows passing through the orifice of weir #27 are oriented directly towards the modified Gate F. In addition, with the narrower width of the excavated pool and the ramps on the upstream and downstream ends of the pool, sand was mobilized down the length of the excavated entrance pool and into the downstream river channel.

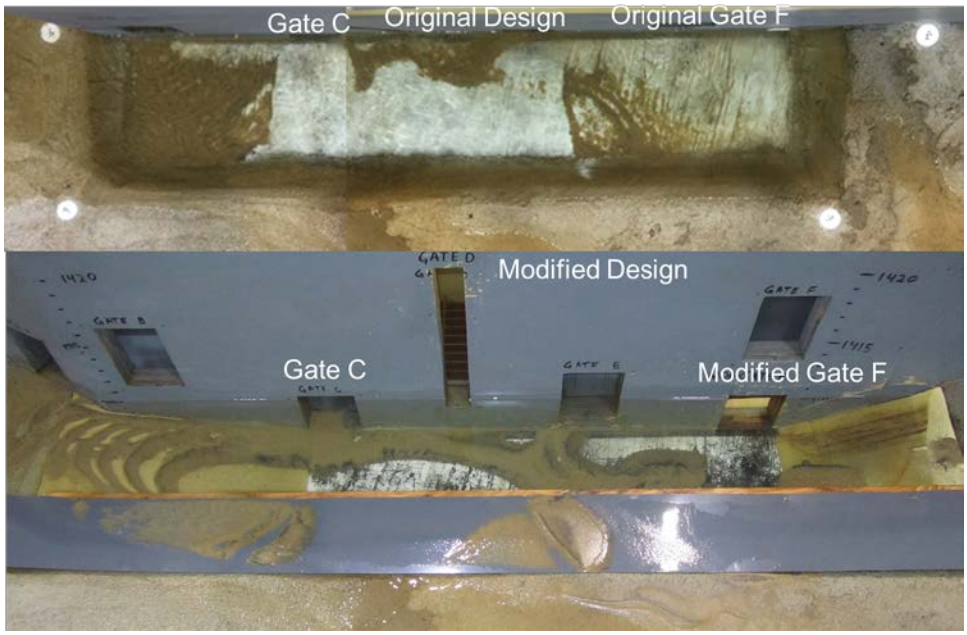


Figure 64. Comparison of sediment passage with original design and modified design of the excavated entrance pool and fish ladder entrance chamber gates at 39 cfs.

Another repeated test was the matrix of pea gravel and 1.5-inch rock placed in the excavated entrance pool. Sediment deposited in the excavated entrance pool passed out into the river channel at either lower flow rates or in greater amounts. By relocating Gate E to a higher elevation, and placing gate F at a lower elevation, an area is cleared around gate F, but a sediment deposit remains between Gate F and Gate D as shown below in Figure 65 and Figure 66. The total volume of this sediment is comparable to the sediment that remained in the area upstream of Gate E of the original design, it is just shifted slightly downstream between Gates F and D.

Figure 65. Modified design test for matrix of pea gravel and 1.5-inch rock with 1870 cfs without dam sluice gate operation.

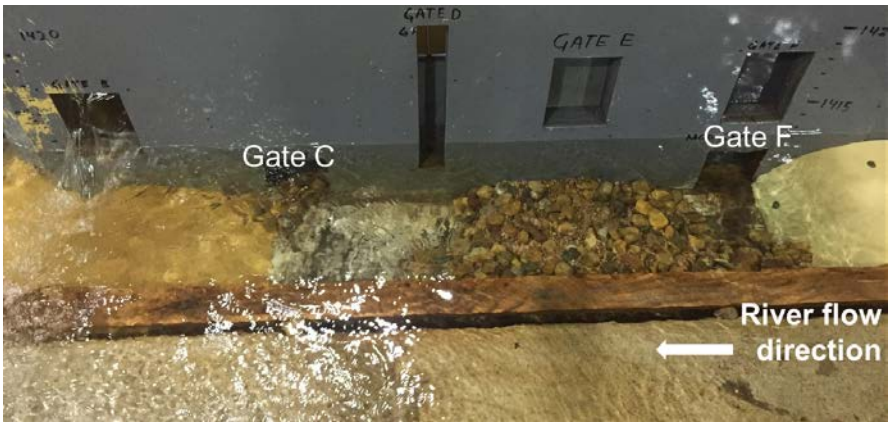


Figure 66. Modified design test for matrix of pea gravel and 1.5-inch rock with 1870 cfs with dam sluice gate operation.

Conclusions

1:5 Scale Fish Screen Model

- Fish screen designs at a 60-degree and 83-degree angle from the horizontal are both able to meet all velocity criteria for flows through the screen.
- The sediment basin shape and elevation was modified to simplify construction, allow a smooth transition to the fish screen, and reduce flow turbulence along the upstream portion of the screen.
- The fish ladder exit chamber shape was modified to reduce a large eddy that formed due to the angular expansion of the walls. This eddy allowed fine sediment to deposit, as well as potentially providing refuge for predatory fish.
- The trash rack at the AWS entrance was changed from a horizontal to vertical orientation for safety reasons and to potentially provide vortex suppression at the AWS intake.
- The sediment basin was effective at capturing sediment carried into the diversion canal from the headworks. The sediment deposits can be effectively flushed during sediment basin sluice gate operation. It is likely that the diversion canal upstream from the basin will fill to some extent with deposited sediment.
- The most effective sluice gate operation for clearing the sediment basin was having the gate fully opened to create free flow conditions under the gate. However, this operation cut off all flow along the fish screen and down the fish ladder.
- Fine sediment that passes the sediment basin is likely to deposit in the fish screen forebay as dunes. During tests in the physical model, the dunes were not as deep as the curb along the bottom of the fish screen. However, prototype conditions may vary due to constraints with scaling sediment transport processes and the limited duration of sediment transport tests that may not have produced equilibrium conditions.
- Fine sediment that passed through the fish screen resulted in small, uniformly distributed deposits behind the screens.
- Fine sediment that entered the fish ladder exit chamber created small deposits in the exit chamber, but no sediment was observed to deposit in the fish ladder pools.

- Approach flow conditions to the tilt gate were not uniform due to the presence of the AWS intake adjacent to the left gate. For this reason, it is recommended that canal flows be measured downstream from the tilt gate structure.

1:8 Scale Fish Ladder Entrance Chamber and Diversion Dam Model

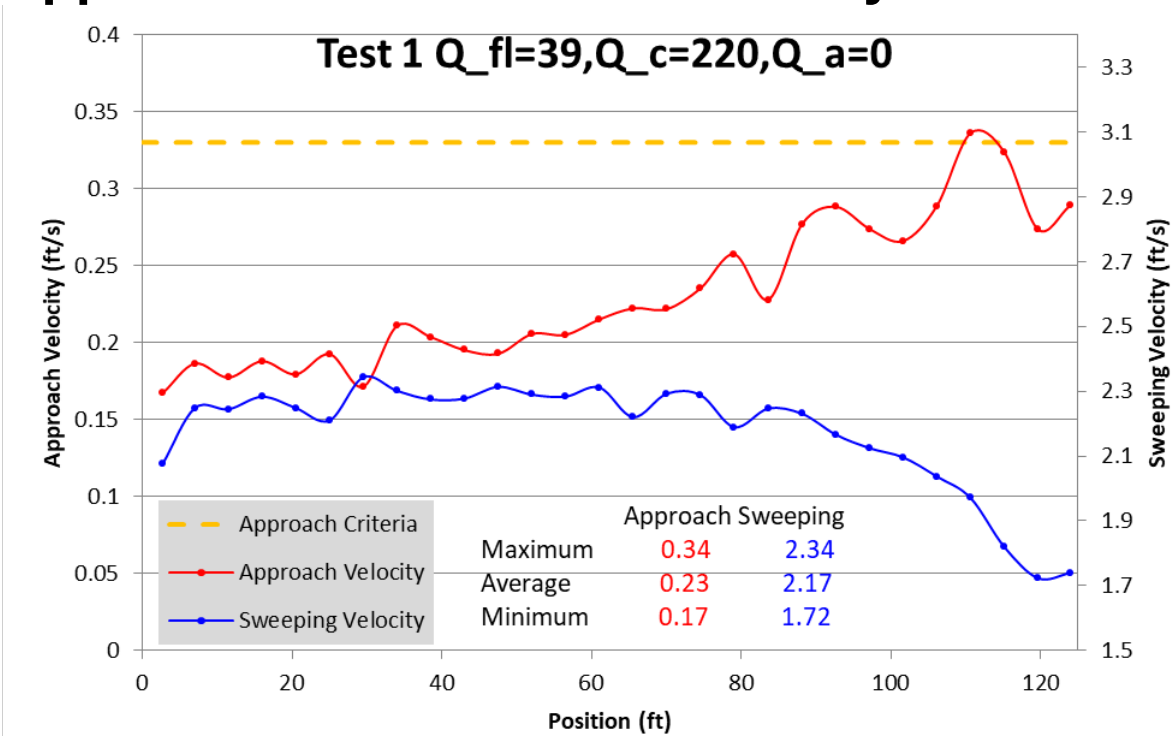
- A flow rate of 39 cfs down the fish ladder provided enough turbulence to prevent sediment from depositing in the fish ladder pools until backwater from the fish ladder entrance chamber slowed the velocity and allowed some deposition.
- Deposition of sediment in the fish ladder pools was not affected by gate operation of the fish ladder entrance chamber gates assuming 1.0 foot WSE differential was maintained.
- Some sediment coming down the fish ladder deposited inside the AWS diffuser sump, but a majority of the sediment passed to the excavated entrance pool through the modified location of Gate F.
- The AWS system should be routinely operated at maximum flow (148 cfs) to mobilize any sediment that deposits inside the fish ladder entrance chamber.
- Gates with lower invert elevations mobilized sediment from the excavated entrance chamber to the downstream river channel.
- The modified design of the fish ladder entrance chamber and excavated entrance pool allowed sand to pass to the downstream channel at a flow rate of 39 cfs (for comparison, the original design required 187 cfs to pass sand).
- Some gates of the fish ladder entrance chamber operated more efficiently than others. Gate E was the least efficient due to flows over the dam following the left bank topography resulting in a trajectory towards the gate.
- The fish ladder entrance chamber contained more gates than are required to achieve a 1.0 foot WSE differential requirement between inside the entrance chamber and the river.
- The top elevation of gate D was extended to 1421 feet to allow free flow and surface attraction at a total river flow of 1870 cfs which resulted in a WSE inside the fish ladder entrance chamber of 1420.1 feet.
- Along the face of the fish ladder entrance chamber, there was a significant drop in the WSE of the river channel due to stagnation as flows exited Gate D. At a total river flow of 1870 cfs, this drop is expected to be approximately 2.0 feet (prototype). An additional drop in the water surface elevation was recorded further downstream near Gate A of 2.0 feet (approximately 50-inch total drop in WSE between the upstream and downstream extent of the fish ladder entrance chamber).

References

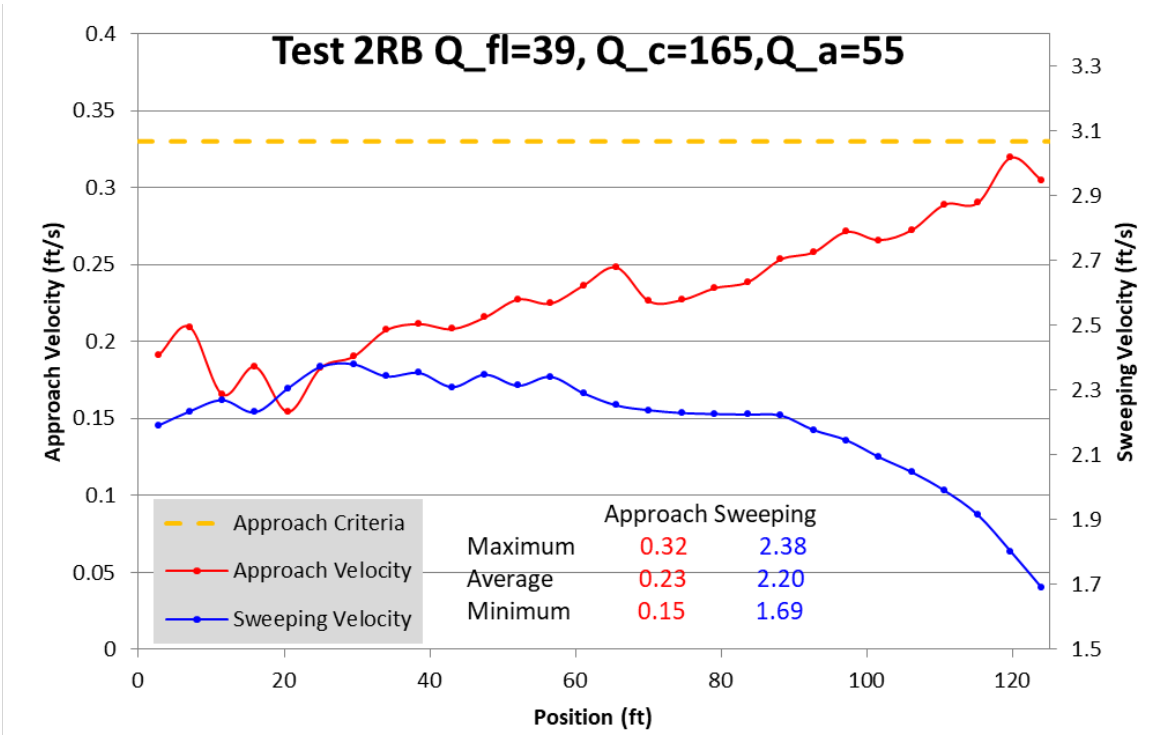
Battle Creek Salmon and Steelhead Restoration Project Memorandum of Understanding, 1999.

National Marine Fisheries Service, 2011, Anadromous Salmonid Passage Facility Design

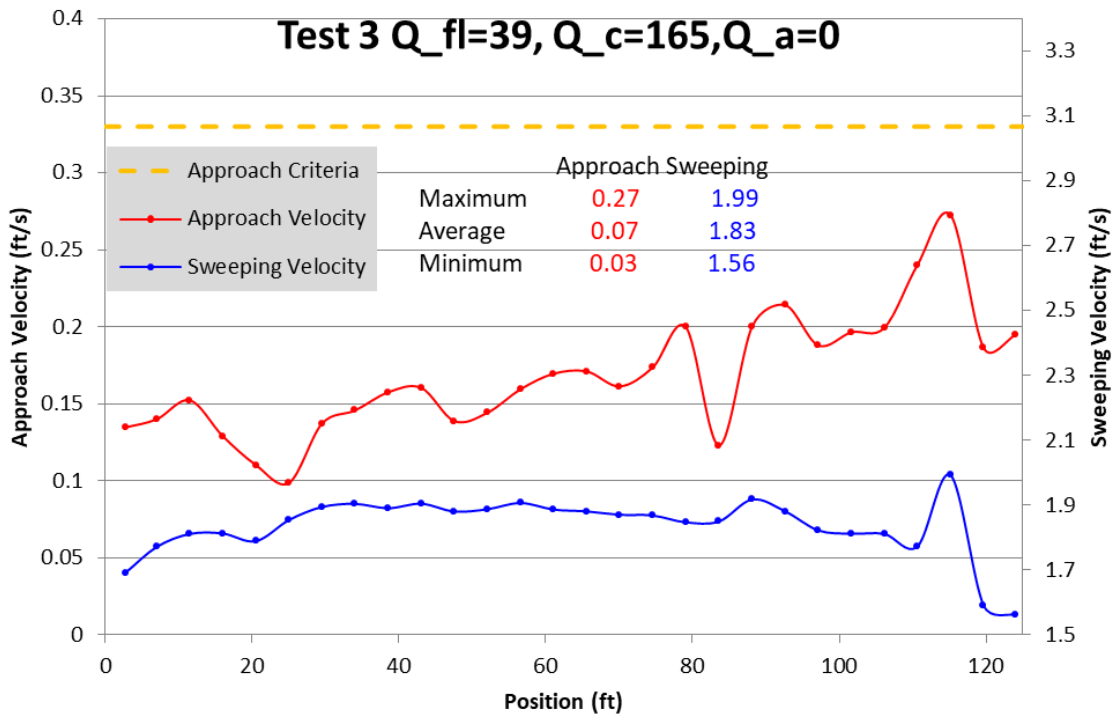
Appendix A: Fish Screen Velocity Plots



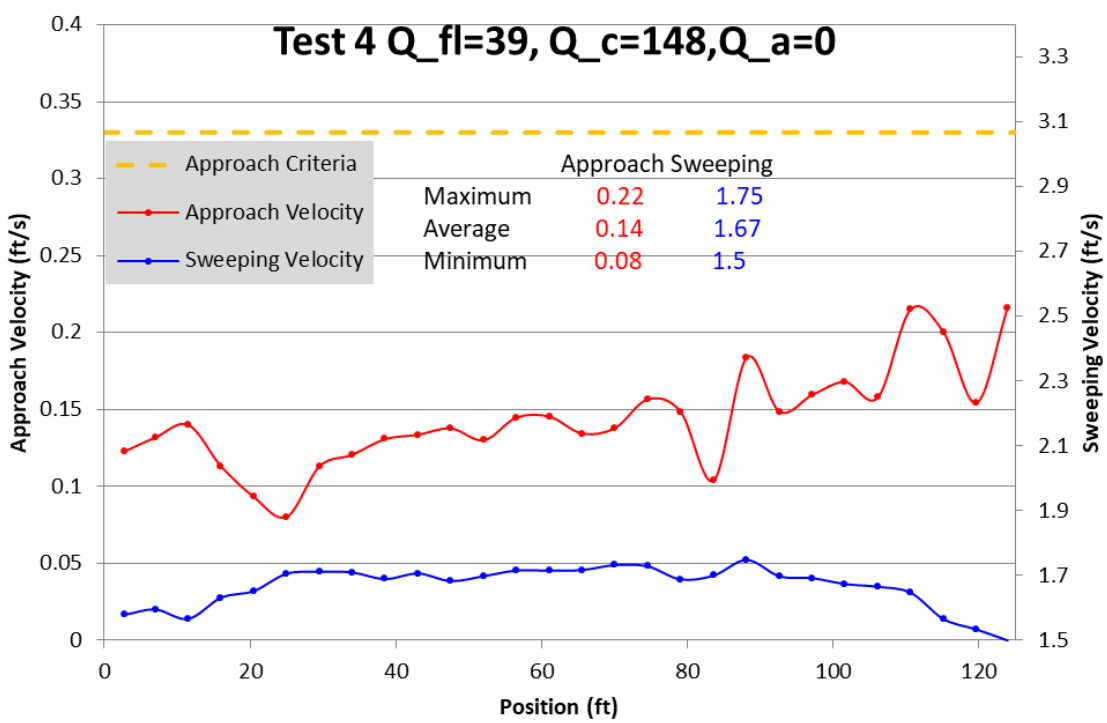
Test 1- Total diversion 259 cfs; fish ladder flow = 39 cfs, canal flow = 220 cfs, auxiliary flow = 0 cfs



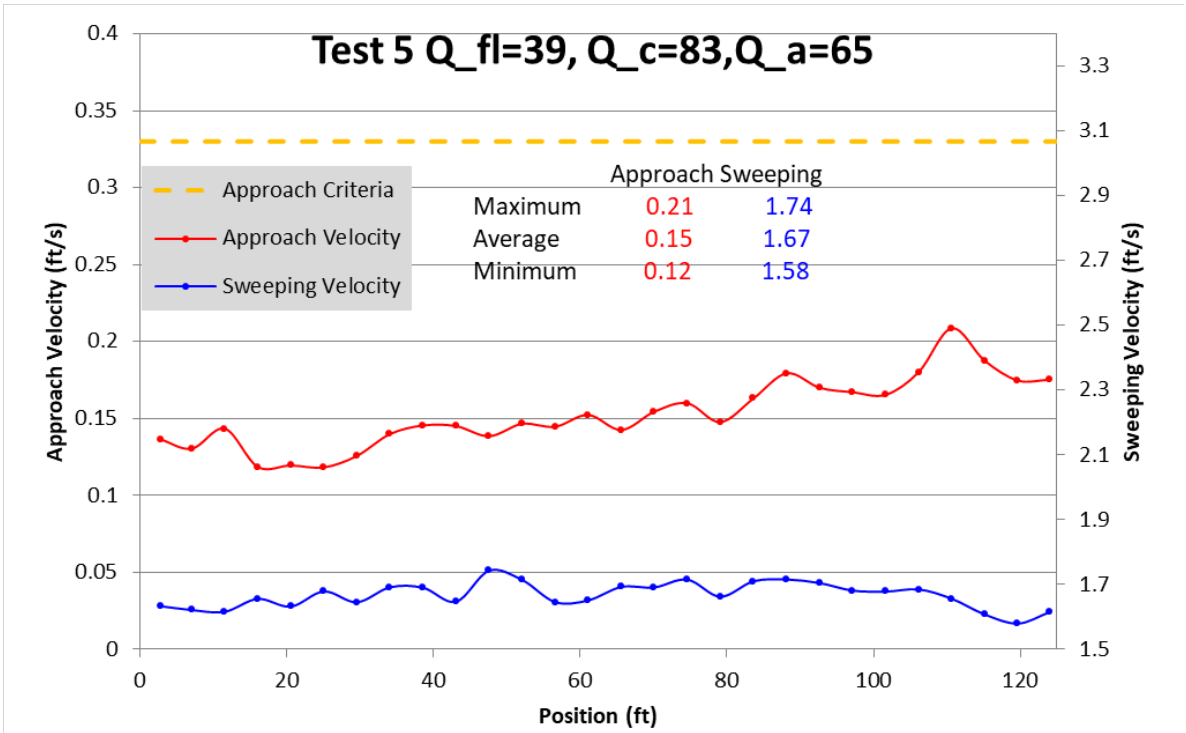
Test 2- Total diversion 259 cfs; fish ladder flow = 39 cfs, canal flow = 165 cfs, auxiliary flow = 55 cfs



Test 3- Total diversion 204 cfs; fish ladder flow = 39 cfs, canal flow = 165 cfs, auxiliary flow = 0 cfs

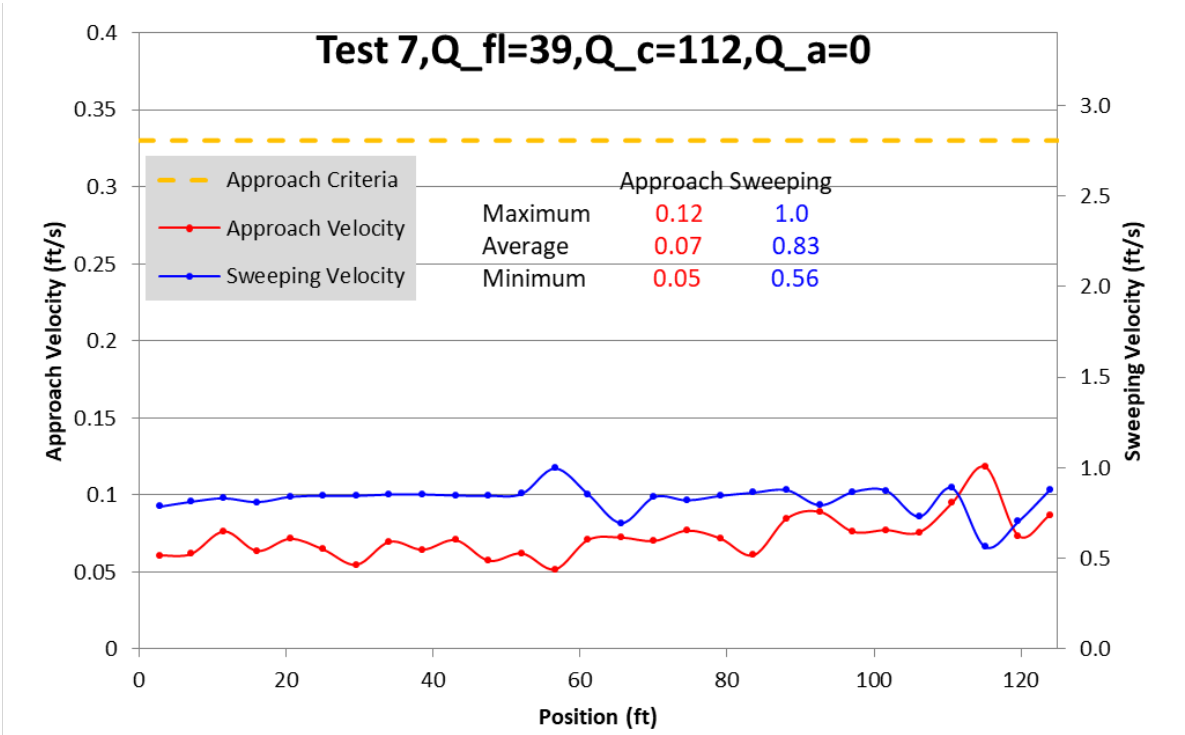


Test 4- Total diversion 187 cfs; fish ladder flow = 39 cfs, canal flow = 148 cfs, auxiliary flow = 0 cfs

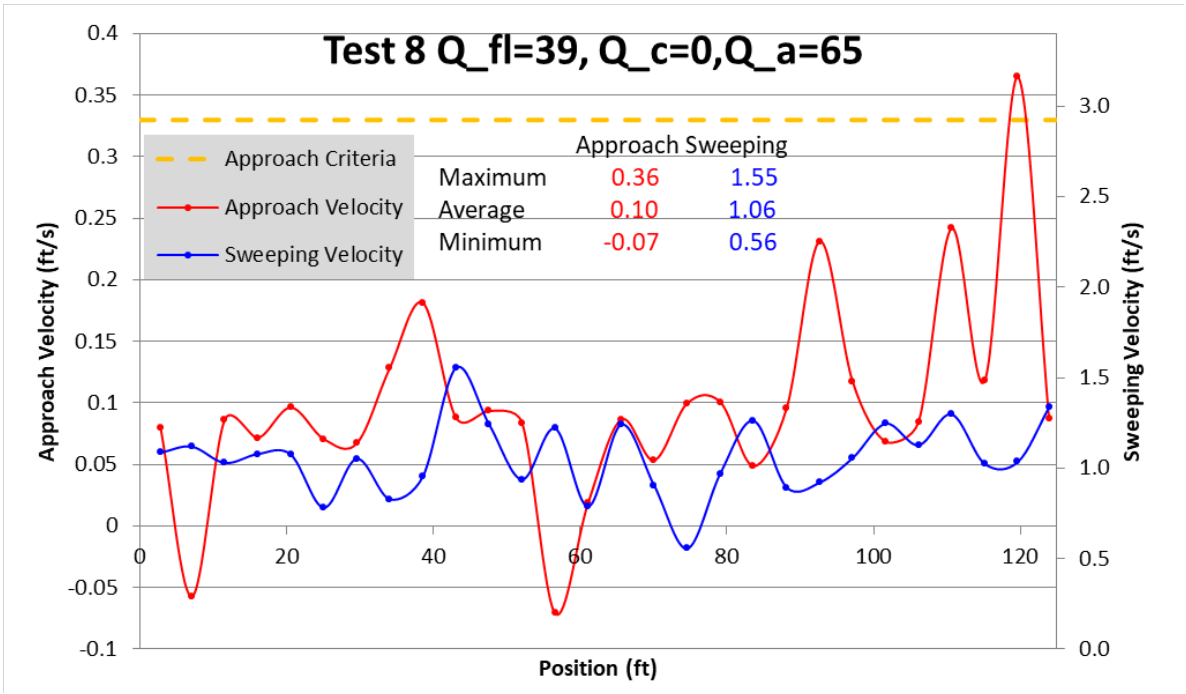


Test 5- Total diversion 187 cfs; fish ladder flow = 39 cfs, canal flow = 83 cfs, auxiliary flow = 65 cfs

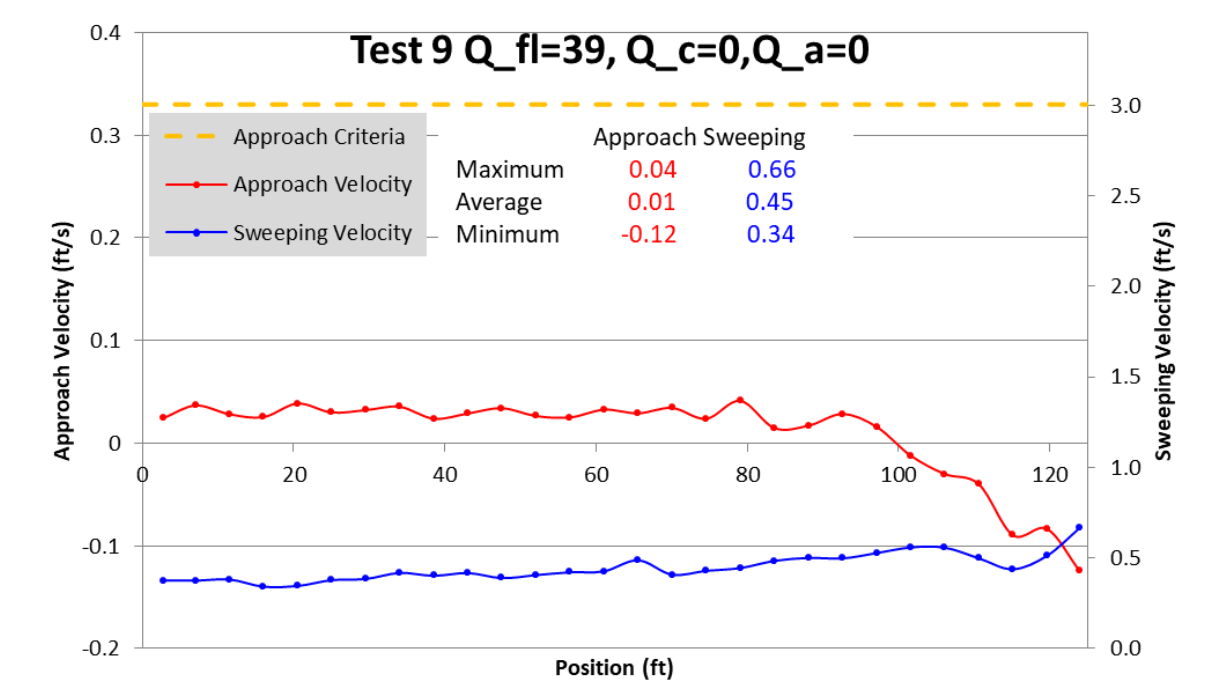
*Test 6 was only able to produce 109 cfs in the initially designed AWS pipe and was replaced with Test 15 when the model AWS was reconfigured and was therefore not presented



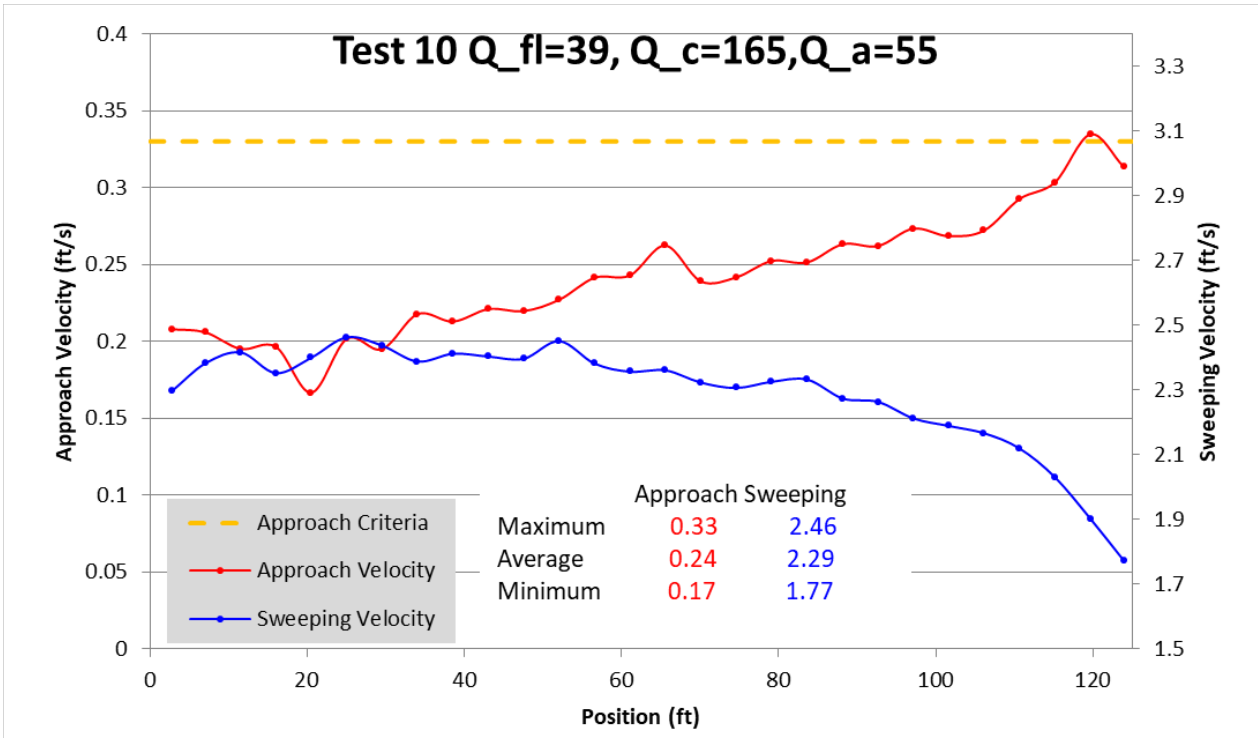
Test 7 - Total diversion 151 cfs; fish ladder flow = 39 cfs, canal flow = 112 cfs, auxiliary flow = 0 cfs



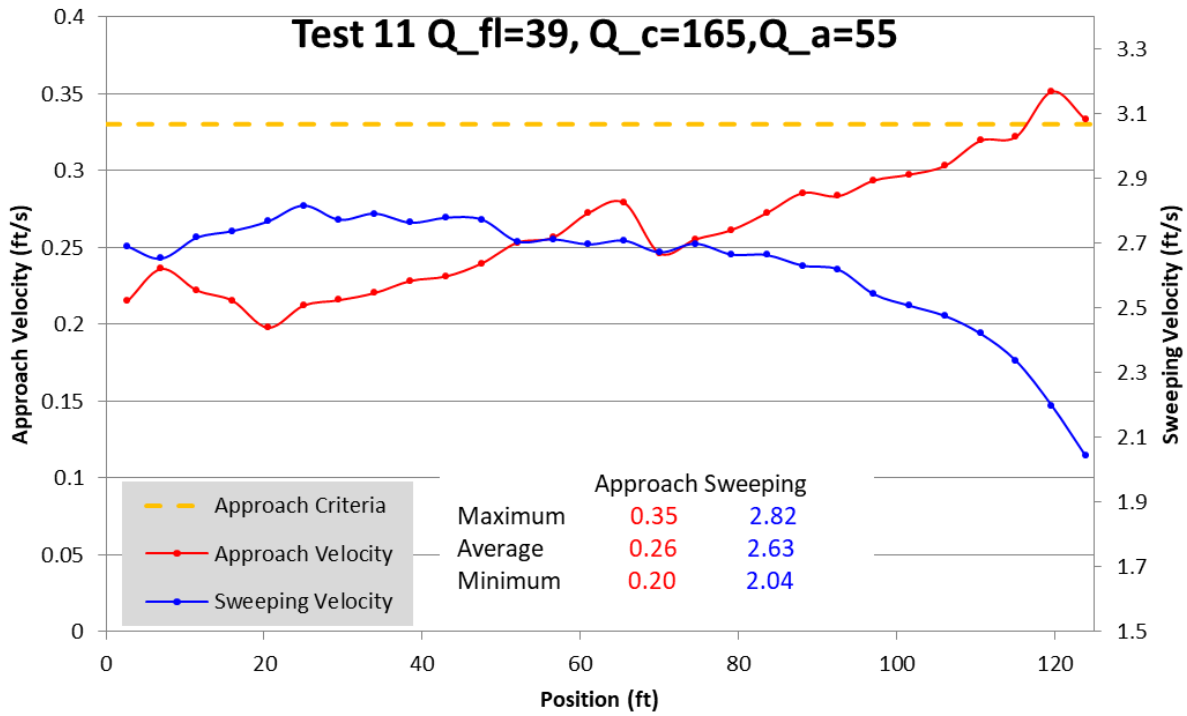
Test 8- Total diversion 104 cfs; fish ladder flow = 39 cfs, canal flow = 0 cfs, auxiliary flow = 65 cfs



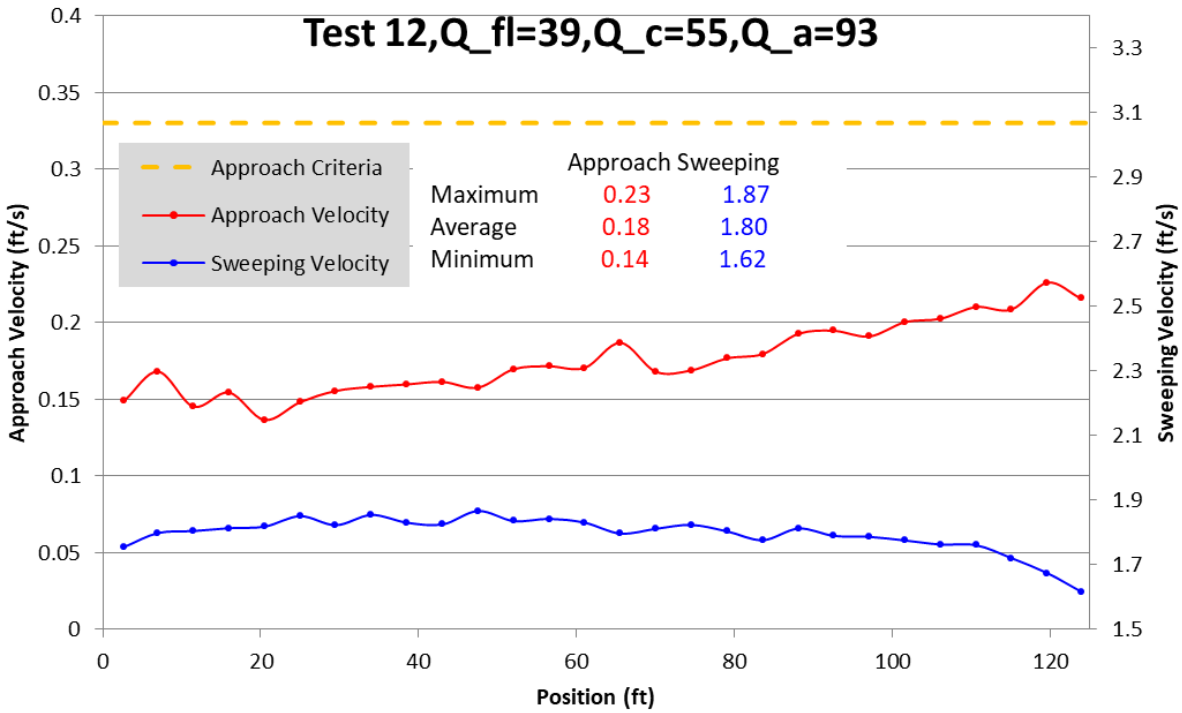
Test 9- Total diversion 39 cfs; fish ladder flow = 39 cfs, canal flow = 0 cfs, auxiliary flow = 0 cfs



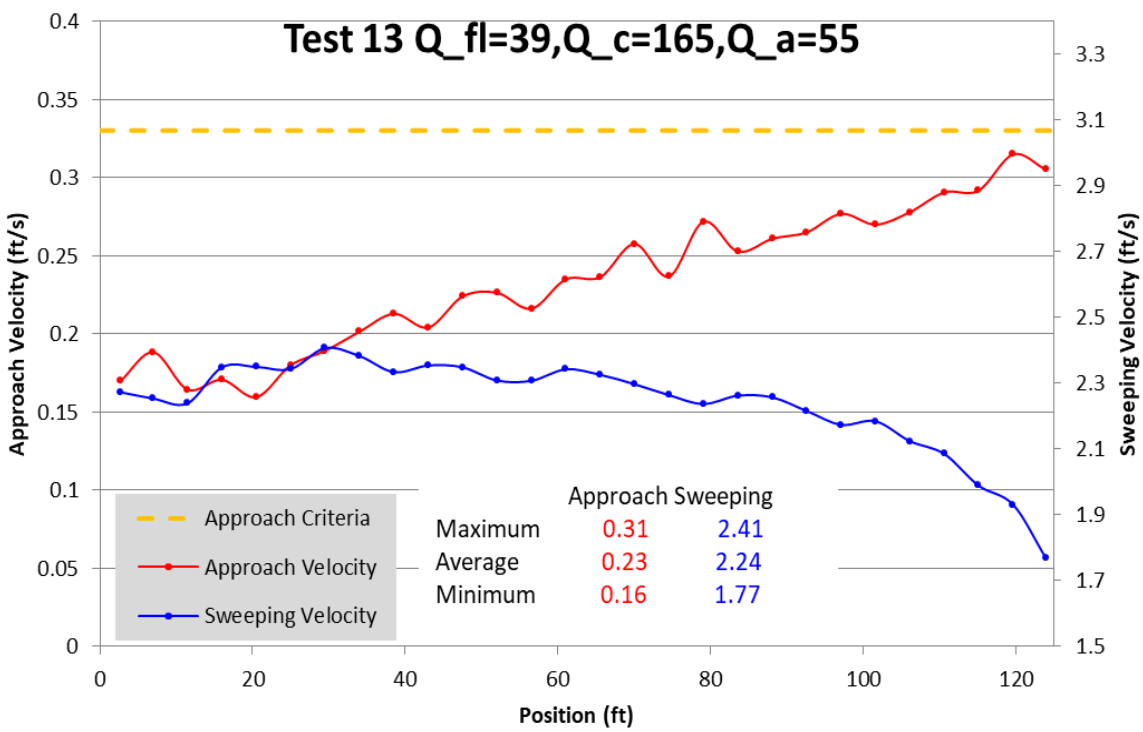
Test 10- Total diversion 259 cfs; fish ladder flow = 39 cfs, canal flow = 165 cfs, auxiliary flow = 55 cfs



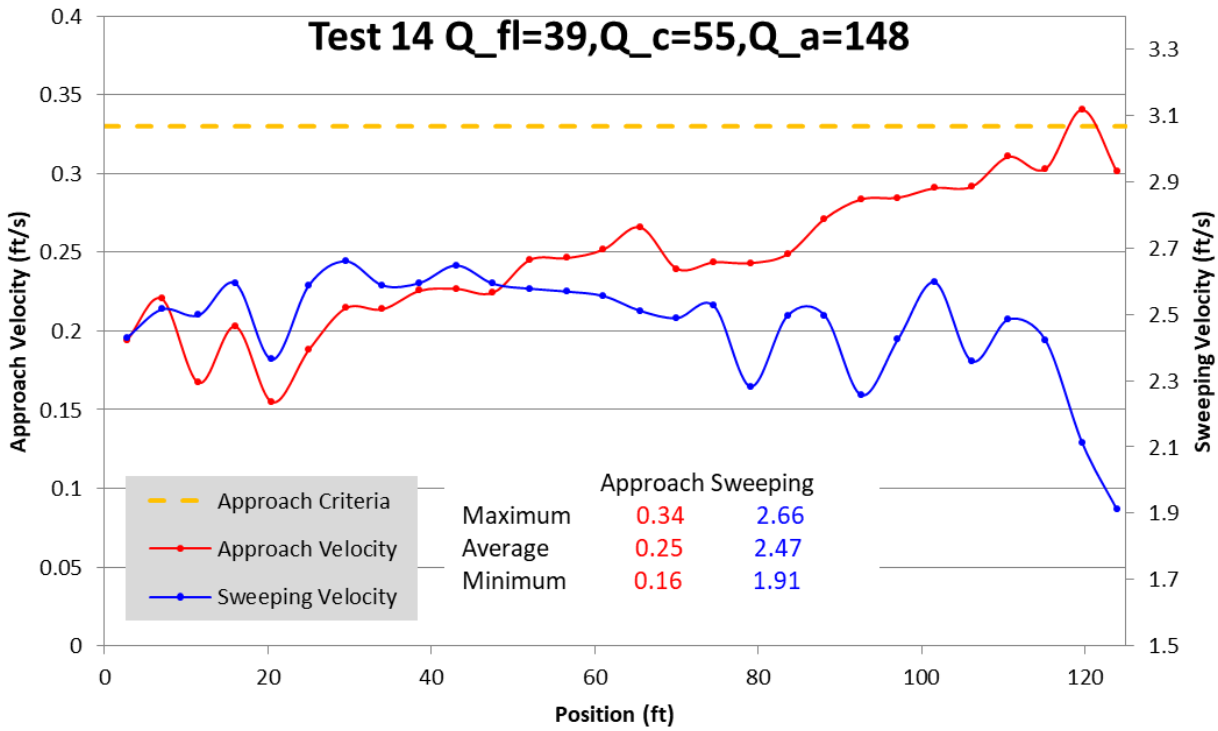
Test 11- Total diversion 259 cfs; fish ladder flow = 39 cfs, canal flow = 165 cfs, auxiliary flow = 55 cfs



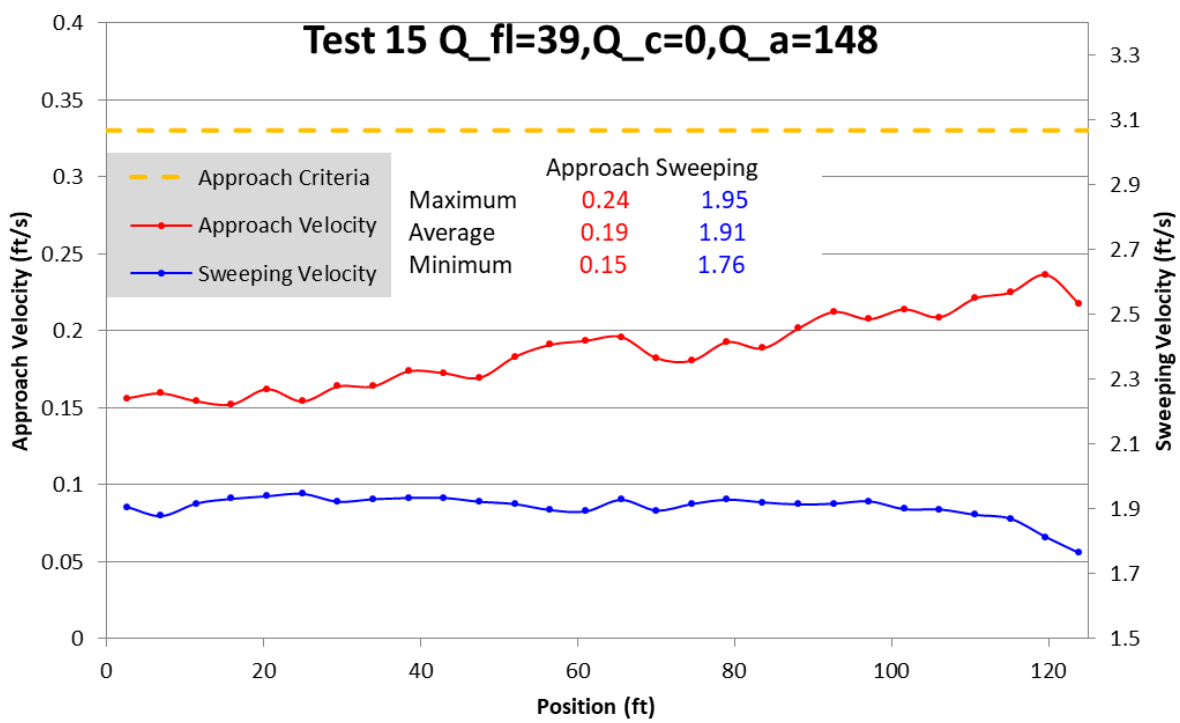
Test 12- Total diversion 187 cfs; fish ladder flow = 39 cfs, canal flow = 55 cfs, auxiliary flow = 93 cfs



Test 13- Total diversion 259 cfs; fish ladder flow = 39 cfs, canal flow = 165 cfs, auxiliary flow = 55 cfs

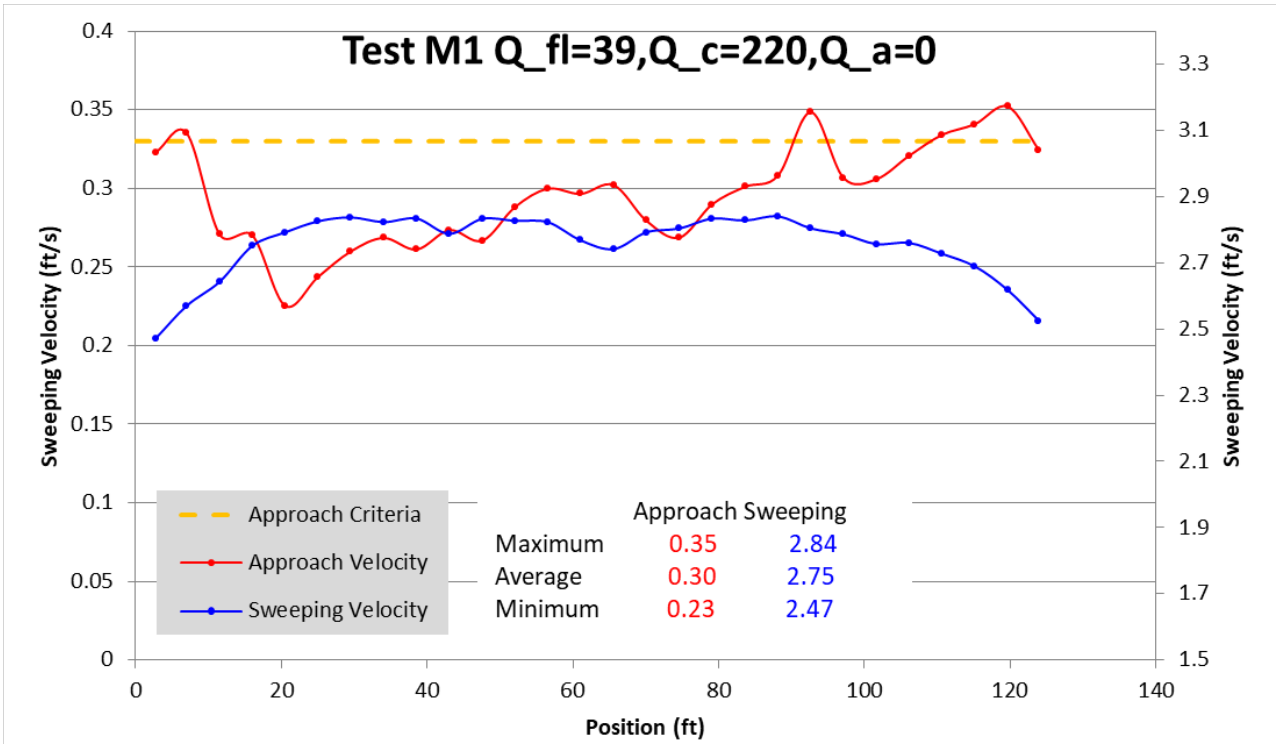


Test 14- Total diversion 242 cfs; fish ladder flow = 39 cfs, canal flow = 55 cfs, auxiliary flow = 148 cfs

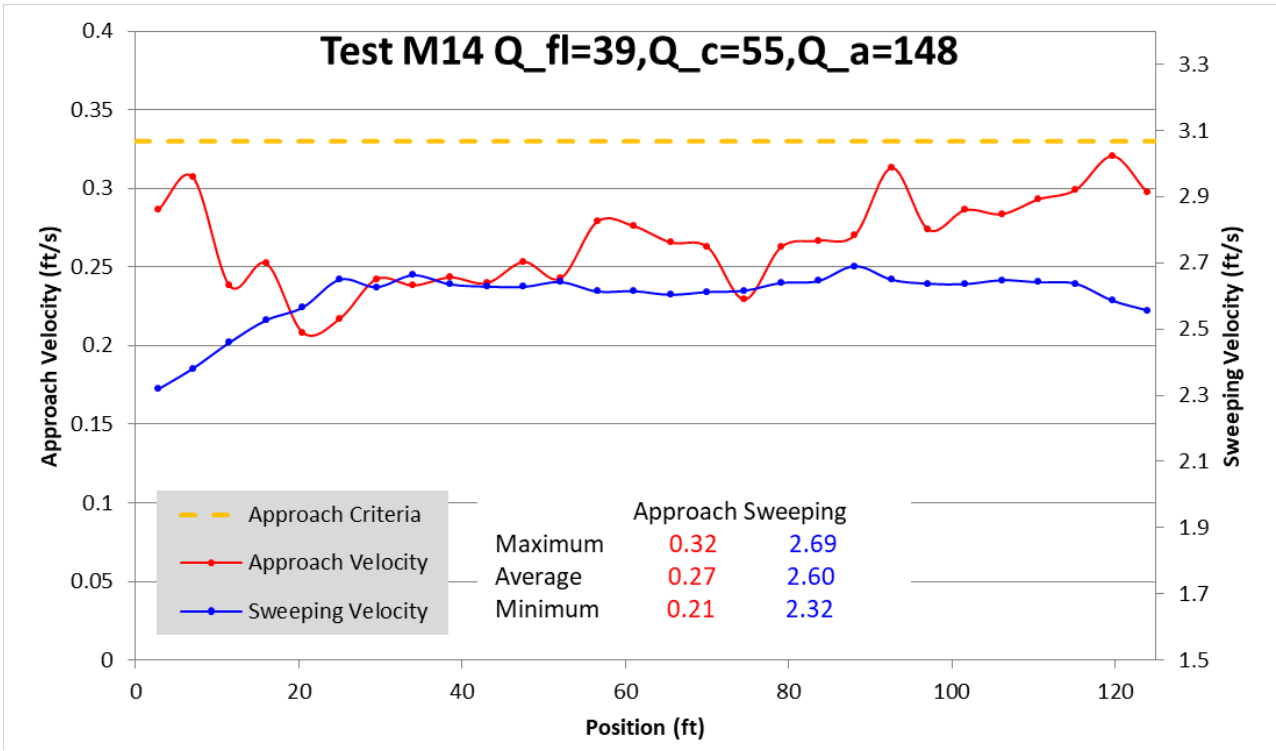


Test 15- Total diversion 187 cfs; fish ladder flow = 39 cfs, canal flow = 0 cfs, auxiliary flow = 148 cfs

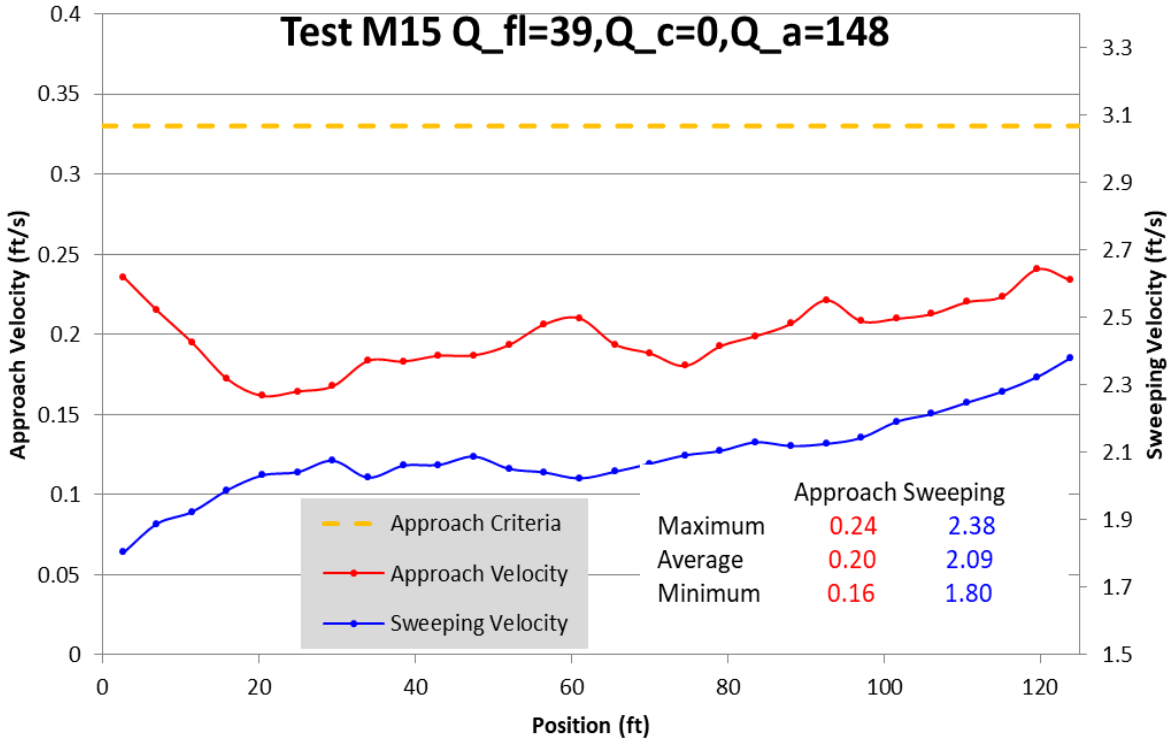
The following tests were repeated after the screen angle was modified from 60° to 83° from horizontal.



Test M1- Total diversion 259 cfs; fish ladder flow = 39 cfs, canal flow = 220 cfs, auxiliary flow = 0 cfs



Test M14- Total diversion 242 cfs; fish ladder flow = 39 cfs, canal flow = 55 cfs, auxiliary flow = 148 cfs



Test M15- Total diversion 187 cfs; fish ladder flow = 39 cfs, canal flow = 0 cfs, auxiliary flow = 148 cfs