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Self-Regulating Articulated Fishway

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A self-regulating articulated fishway was evaluated at the Bureau of Reclamation's Hydraulic Laboratory. The fishway is designed to be installed at low head diversion structures where the reservoir water surface elevation fluctuates regularly by less than 3 ft. The fishway will adjust to the upstream change in water surface elevation to provide a constant fishway discharge, without adversely affecting the hydraulics in the fishway.

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Self-Regulating Articulated Fishway

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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

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

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Hydraulic Laboratory Reports

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GLOSSARY OF SYMBOLS

BOR	U.S. Bureau of Reclamation
CFD	Computational Fluid Dynamics
ODF&W	Oregon Department of Fish and Wildlife
RWS	Reservoir Water Surface
WSE	Water surface elevation

Project Background

Traditional Fishways are designed with the upstream end of the fishway fixed at a set elevation. Over a range of headwater elevations, varying amounts of flow pass through the fishway if the upstream end is not gated. During high river flows, the water surface elevation upstream of the fishway increases and an increased flow is passed down the fishway. At small diversion dams, this can limit the amount of flow available for diversion. The inability to design for a constant fishway flow over the range of headwaters on an ungated fishway often prohibits fishway construction on small diversion dams or results in frequent closure of the fishway by irrigators that believe the fishway is taking too much water. Fishways may be shut down during high diversion periods or flow may be restricted with weir boards, that can impede fish passage.

A self-regulating articulated fishway is being developed at Reclamation's Hydraulics Laboratory in Denver, CO. A self-regulating fishway self-adjusts to changing headwater elevations in order to maintain a more consistent flow through the fishway. By adjusting to the changing headwater a nearly constant flow passes through the fishway. A self-regulating articulated fishway can be used at small diversion dams with water surface fluctuations between about 1 to 3 ft.

In a typical fishway the upstream end of the fishway (fishway exit) has a fixed elevation. When the upstream headwater increases, flow through the fishway also increases. In a self-regulating articulated fishway design, the downstream half of the fishway is at a fixed elevation and the upstream half can pivot around a hinge in the middle of the fishway (Figure 1 through Figure 3). In this manner, when the headwater increases in elevation the upstream end of the fishway also increases in elevation and the flow through the fishway remains constant.

The Klamath Basin Area Office and the Oregon Department of Fish and Wildlife (ODF&W) share a need to develop a fishway suitable for passage of endangered sucker species and other native fish indigenous to highly regulated streams in the west. These fishways need to be able to pass a constant flow over a range of headwater elevations. After research is completed in a laboratory setting, future testing will be carried forward and tested at a field site by ODF&W with assistance from Reclamation.

Model Setup

A duel vertical slot technical fishway with 9 pools was tested in the hydraulics laboratory. The width of the fishway was 2 ft and the length of each pool was 2 ft. The depth of the fishway was 1.5 ft. See Figure 1 through Figure 3 detailing the model layout. This model can be scaled up to larger sizes of fishways. In this study, the downstream half of the fishway was kept at a constant slope of 3 degrees for all tests. The upstream half of the fishway was tested at slopes ranging from 0.2 to 5.7 degrees. Initially the slope of the upstream half of the fishway was controlled manually with a chain hoist. Different methods of self-regulation were subsequently evaluated in phase 2 of the study.

Flow rates tested ranged from 0.35 ft^3/s to 1.05 ft^3/s. Flow rates into the model were calculated with the laboratory's venturi flow measurement system. The downstream tailwater was manually controlled with stop logs to maintain a water surface drop across the most downstream baffle of about 1.6 inches. Figure 1 shows how the downstream half of the fishway penetrates through the dam. The hinged portion of the fishway is just upstream of the axis of the dam, therefore allowing the upstream half of the fishway to adjust with varying upstream Reservoir Water Surface (RWS) elevation.

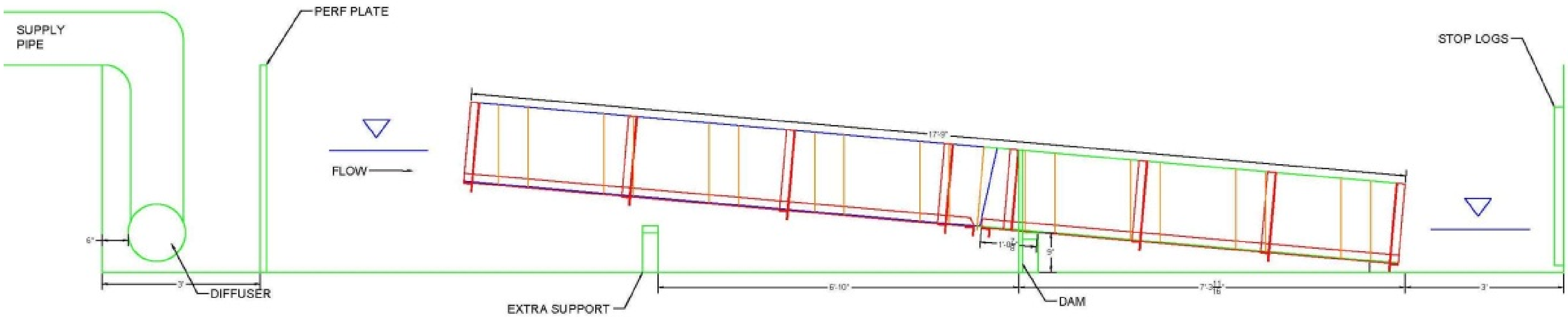

Figure 1. Model fishway setup showing the supply water, upstream WSE, attachment to the dam structure, and tailwater controls with stop logs.

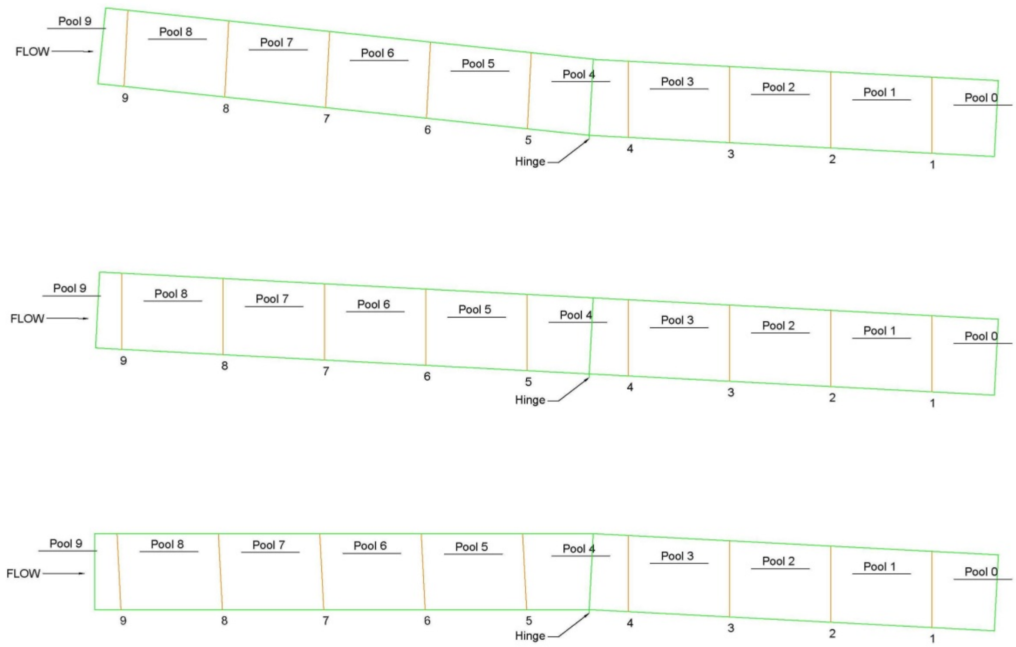

Figure 2. Elevation view of the articulated fishway. Notice the hinge in the middle allowing the upstream half of the fishway to rotate up (top view) and down (bottom view) with the changing upstream WSE. Also note the naming convention of the pool and baffle numbering.

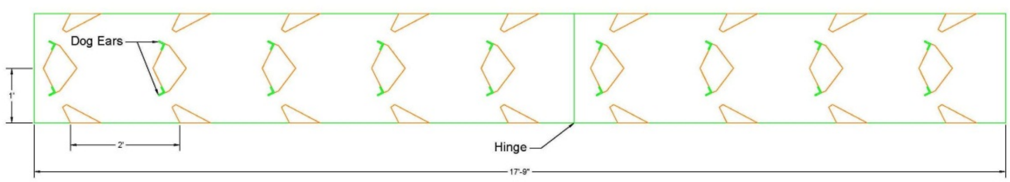

Figure 3 Plan view of the duel vertical slot fishway.

Objectives:

- Evaluate the hydraulic conditions in the fishway over a range of upstream fishway slopes with a constant downstream slope).
- Evaluate the hydraulic conditions in the fishway over a range of flow rates.
- Design ways to self-regulate the fishway.

- Compare physical model study results with computational fluid dynamics (CFD) results.

Investigation and Analysis

Baffle Dog Ears

A duel vertical slot fishway was used for the self-regulating articulated fishway design. During the initial testing flow instabilities within the fishway developed that caused inconsistent water surface drops from pool to pool. Before testing of the articulated design could begin, a modification to the duel vertical slot fishway was needed. To produce a more uniform flow condition "dog ears" were added to the baffle center pier as shown in Figure 4. Without the dog ears the water surface drop per baffle oscillated between a large drop and small drop as shown in Figure 5.

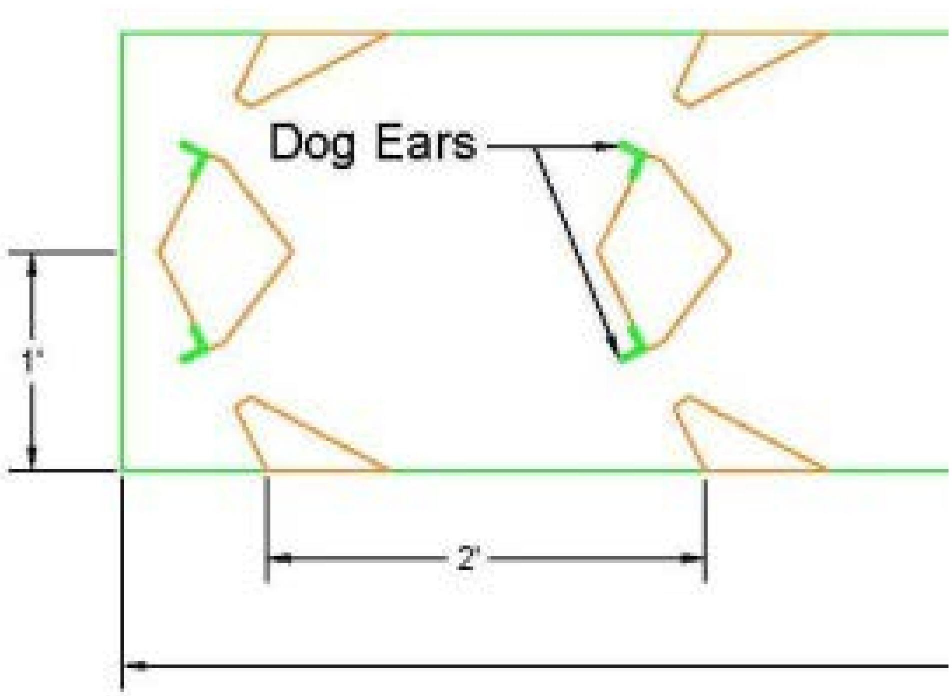

Figure 4. Plan view detail showing the "dog ear" extensions that were added to the center baffles after initial testing showed flow instabilities in the fishway.

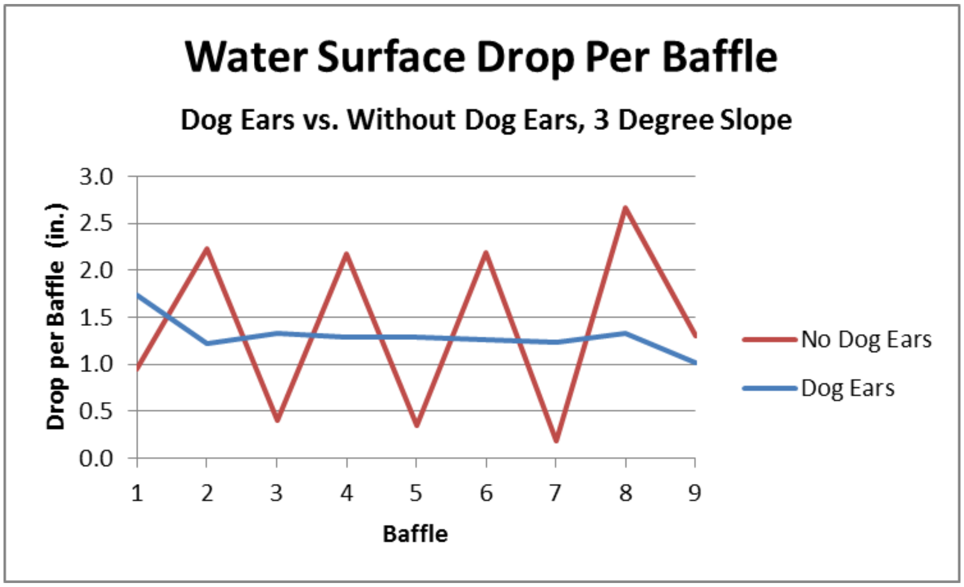

Figure 5. Water surface drop per baffle, with and without dog ears for a 3 degree slope. Notice that without the dog ears the water surface drop across the odd numbered baffles is much lower than the even numbered baffles.

This oscillation between a large drop and small drop is caused by the flow patterns that develop in the pools. In the even numbered pools the water entered the upstream end of the pool with the velocity vector directed towards the outside of the pool. At the downstream end of the pool the water recirculated toward the center of the fishway. In the odd numbered pools the water recirculated in the opposite direction. The water entered the upstream end of the pool with the velocity vector directed towards the center of the fishway. At the downstream end of the pool the water recirculated toward the outside of the fishway (see Figure 6). For example, the resulting water surface drop across baffle 6 (from pool 6 to pool 5) is a large drop (Figure 5).

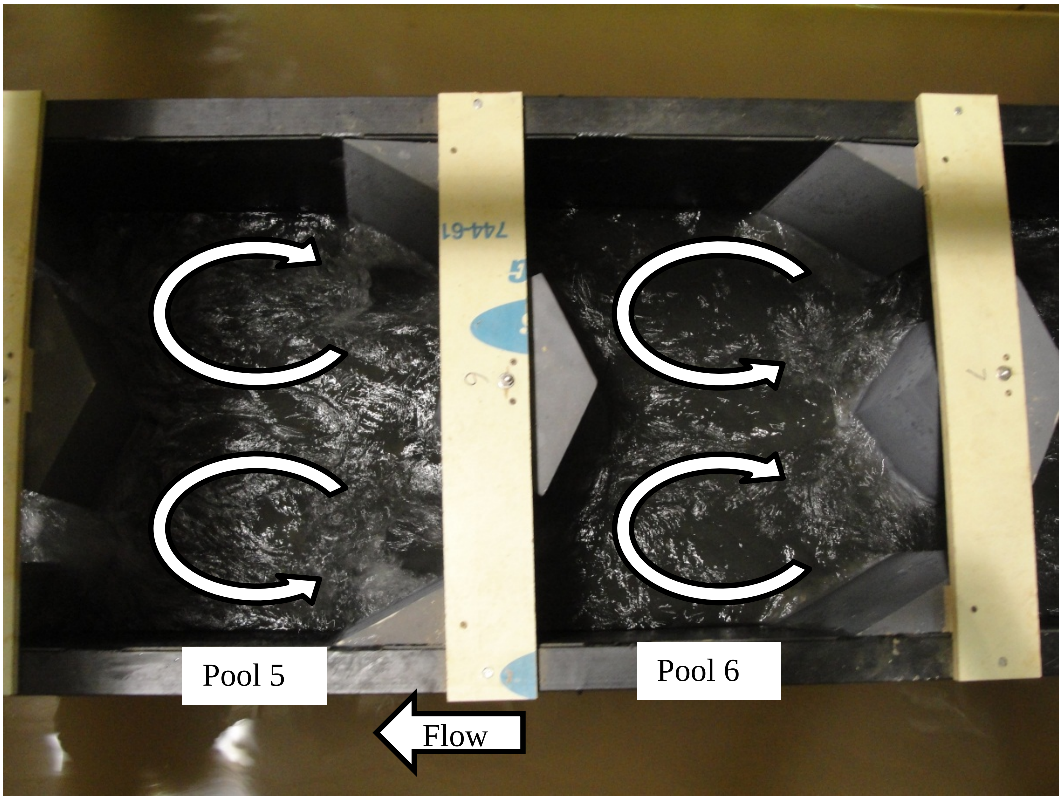

Figure 6. View of pools 6 and 5 showing the different flow patterns that develop in each pool without the dog ears. Q=0.6 ft^3/s, upstream slope= 3 degrees, downstream slope= 3 degrees.

After the dog ears were added to the baffles the flow recirculation in every pool was the same as in pool 5. The water entered upstream end of the pool with the velocity vector directed towards the center of the fishway. At the downstream end of the pool the water recirculated toward the outside of the fishway (see Figure 7). This caused the water surface drop from pool to pool to be uniform (see Figure 5). In the duel slot vertical fishway design, the baffle dog ears are required in order to achieve uniform water surface drop across each baffle. The remainder of the study included dog ears for all tests.

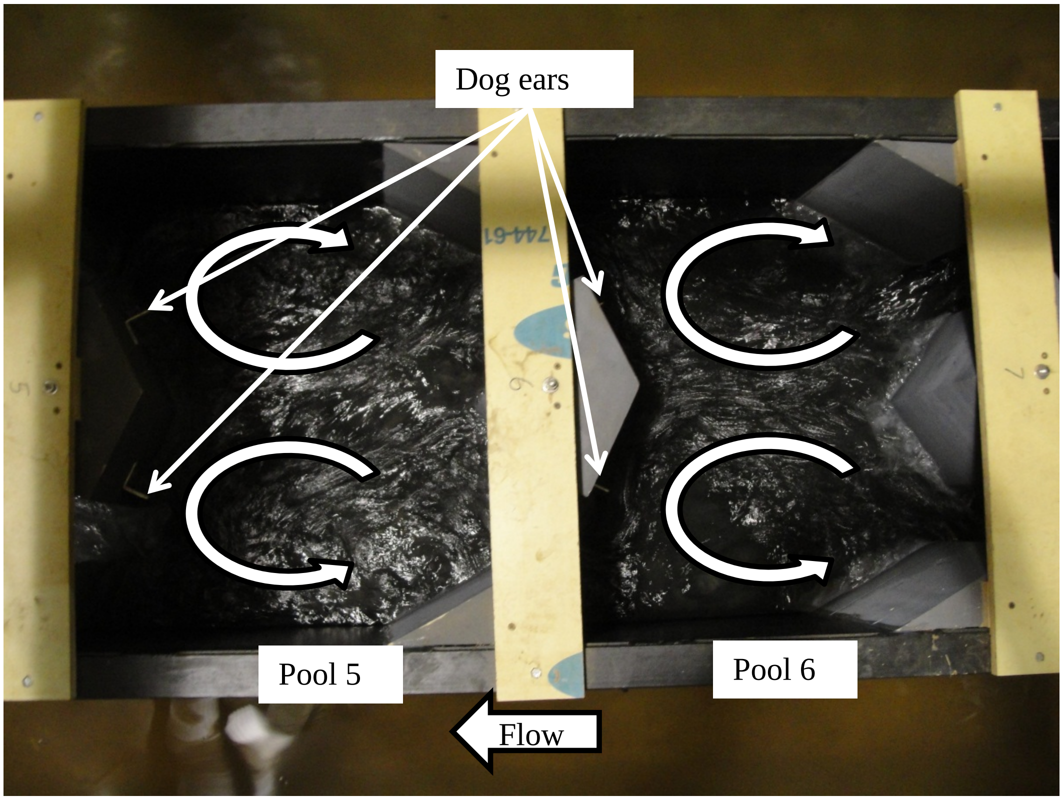

Figure 7. View of pools 6 and 5 showing the same flow patterns that develop in each pool with the dog ears. Notice the flow recirculation pattern is the same in both pools. Q=0.6 ft^3/s, upstream slope= 3 degrees, downstream slope= 3 degrees.

Hydraulic Conditions for Varying Slopes

A major objective of this study was to investigate hydraulic conditions when the fishway has two different slopes along its length. For all tests the downstream half of the fishway was at a constant 3 degree slope. The fishway was tested with the upstream half at slopes ranging from 0.2 through 5.7 degrees. Pool WSEs and visual observations were made for each test configuration. WSE was measured with an ultrasonic water level sensor (Massa products Corporation, Hingham, MA). Velocity through the slot was measured with a Swoffer 3000 (Swoffer Instruments, Seattle, WA). Energy Dissipation Factors (EDF) were calculated for each configuration using the following equation:

$$EFD = \frac{\gamma}{(V_{pool})(Q)(h)}$$

Where:

EFD= Energy Dissipation Factor

γ= Unit weight of water (62.4 lb/ft^3)

V_{pool}= Volume of the pool at minimum tailwater (ft^3)

Q= Flow rater entering the pool (ft^3/s)

h= Total energy head of the flow entering the pool (ft) (velocity head plus drop)

Figure 8 shows the WSE in each pool for varying upstream slopes with a constant discharge of 0.6 ft^3/s. Pool 9 is the forebay and pool 0 is downstream of the fishway (see Figure 2). Since the downstream slope remained constant, the downstream individual pool WSE does not change when the upstream slope was changed. However, when the upstream slope increases or decreases the upstream WSE consequently increases or decreases, respectively.

Figure 9 shows the water surface drop per baffle over the range of upstream slopes. This figure also shows illustrates how the water surface drop per individual baffle does not change for the downstream baffles. When the upstream slope is greater than 3 degrees (equivalent to the downstream slope), the water surface drop is greater than those drops in the downstream half of the fishway. When the downstream slope is less than 3 degrees, the water surface drop is less than those drops in the downstream half of the fishway.

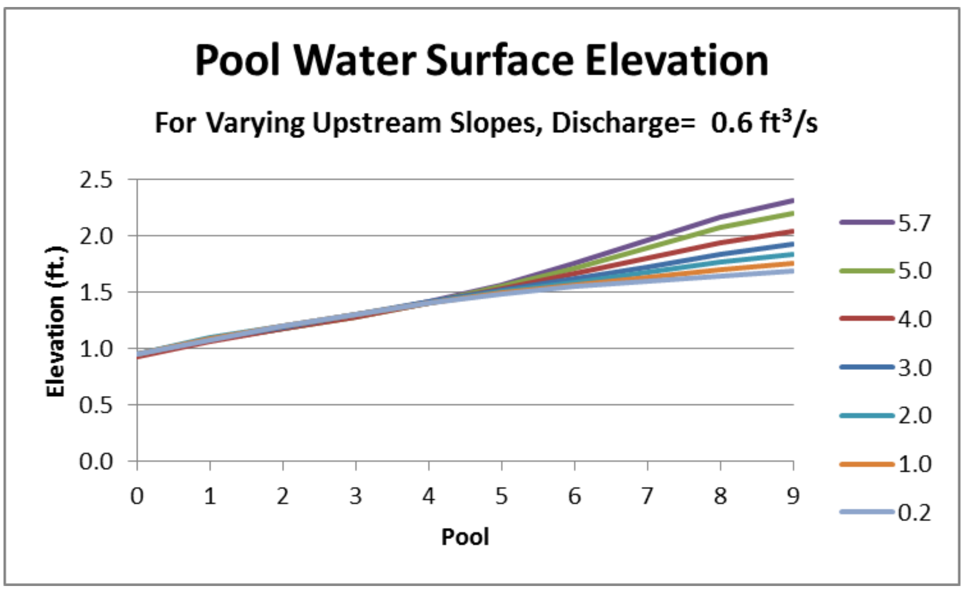

Figure 8. Pool WSE through the fishway for varying upstream slopes, discharge = 0.6 ft^3/s

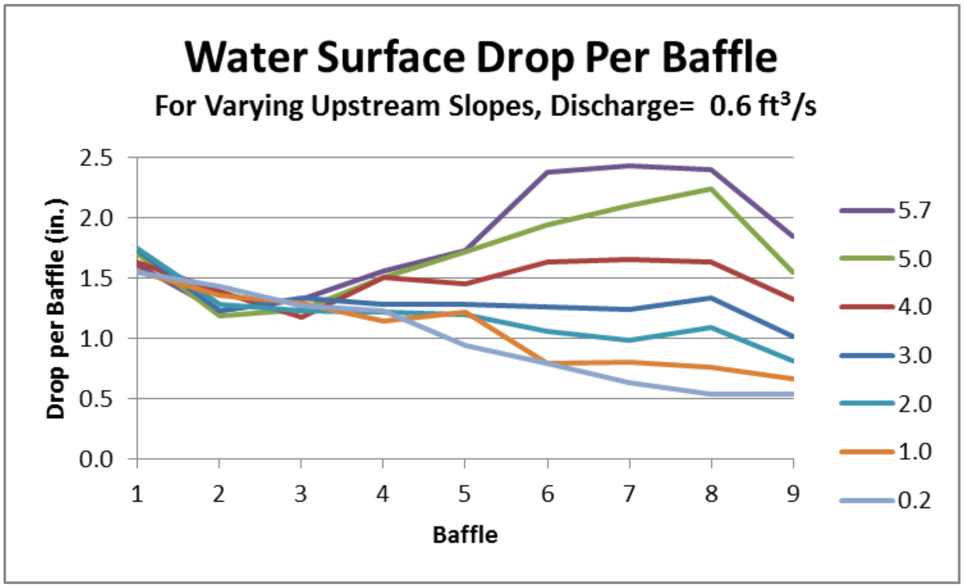

Figure 9. Water surface drop, in inches, per baffle for varying upstream slopes, discharge= 0.6 ft^3/s.

Slot velocity measurements reflected the same pattern as the water surface drop per pool. Slot velocities in the upstream half of the fishway increased as the slope increased, and decreased as the slope decreases (see Figure 10). As expected, since the EDF is a function of total energy head and discharge, the calculated EDF follows a similar trend as the water surface drop per baffle and baffle slot velocity (see Figure 11).

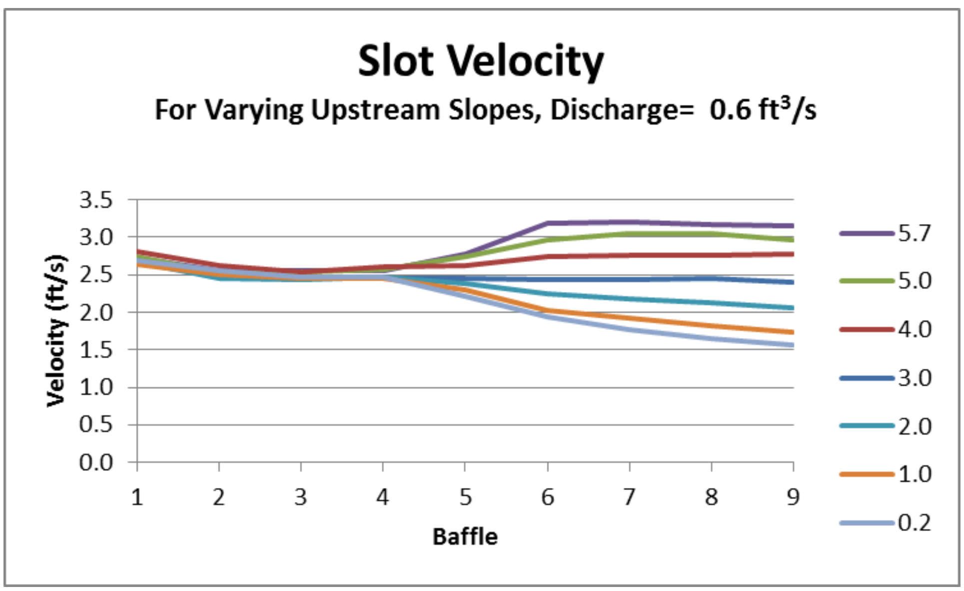

Figure 10. Baffle Slot velocity for varying upstream slopes, discharge= 0.6 ft^3/s.

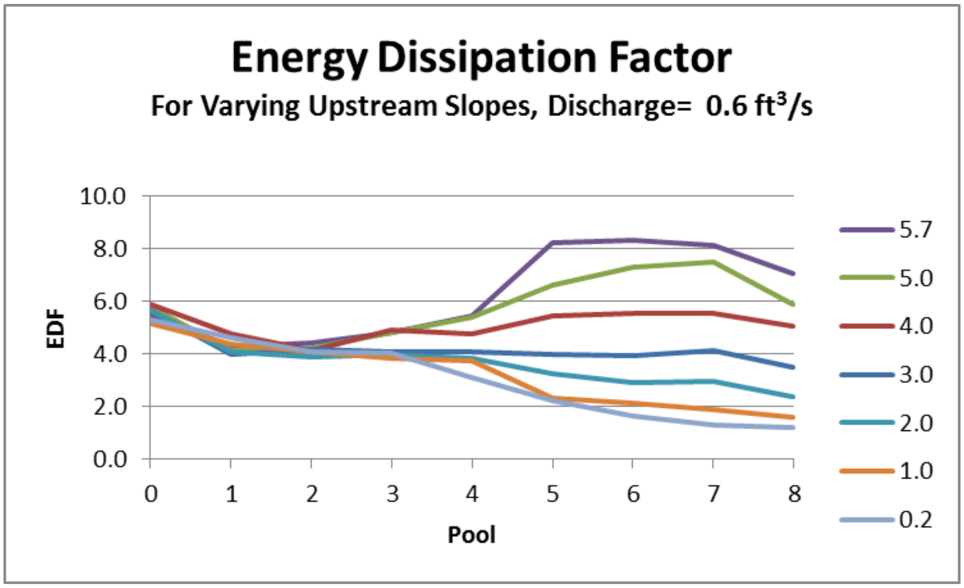

Figure 11. Energy Dissipation Factor for varying upstream slopes, discharge= 0.6 ft^3/s.

Visual comparisons and video observations for differing upstream slopes showed identical flow patterns (see Figure 12 and Figure 13). Over the ranges of slopes tested, the only visual difference in hydraulics was a greater water surface drop and greater slot velocity in the upstream half of the fishway for steeper slopes. For shallower slopes the upstream half of the fishway had smaller water surface drops and smaller slot velocities. Throughout the range of slopes tested, there were no adverse hydraulic conditions that would hinder fish passage. No hydraulic jumps developed in the fishway. However, the fishway should be designed so that the maximum pool-to-pool drop and slot velocity does not exceed the target species design criteria. Tested flow rates did not adversely affect hydraulics of the articulated fishway. Therefore, results are only shown for one tested flow rate.

Figure 12. Pools 6 and 5, upstream slope= 0.2 degrees, discharge=0.6 ft^3/s. Visual flow patterns were identical for varying upstream slopes.

Figure 13. Pools 6 and 5, upstream slope= 3 degrees, discharge= 0.6 ft^3/s. Visual flow patterns were identical for varying upstream slopes.

Fishway Flow Rate

The flow rate calculation in a duel vertical slot fishway is complex because of the submergence effects the pools have on the fish exit or upstream end. In phase 1 of the model study, flow entering the model was measured with the laboratory's venturi flow measurement system. All flow that entered the model went down the fishway. Due to limited resources a full range of data collection varying slope and head was not possible. Model data were collected for a constant flow rate of 0.6 ft^3/s for slopes varying from 0.2 degrees to 5.7 degrees. Also, data were collected for a constant slope of 3 degrees with varying flow rates from 0.35 ft^3/s to 1.05 ft^3/s. From this data, a series of ratings curves were developed for different fishway slopes relating flow vs. head (head is defined as the RWS - fishway invert).

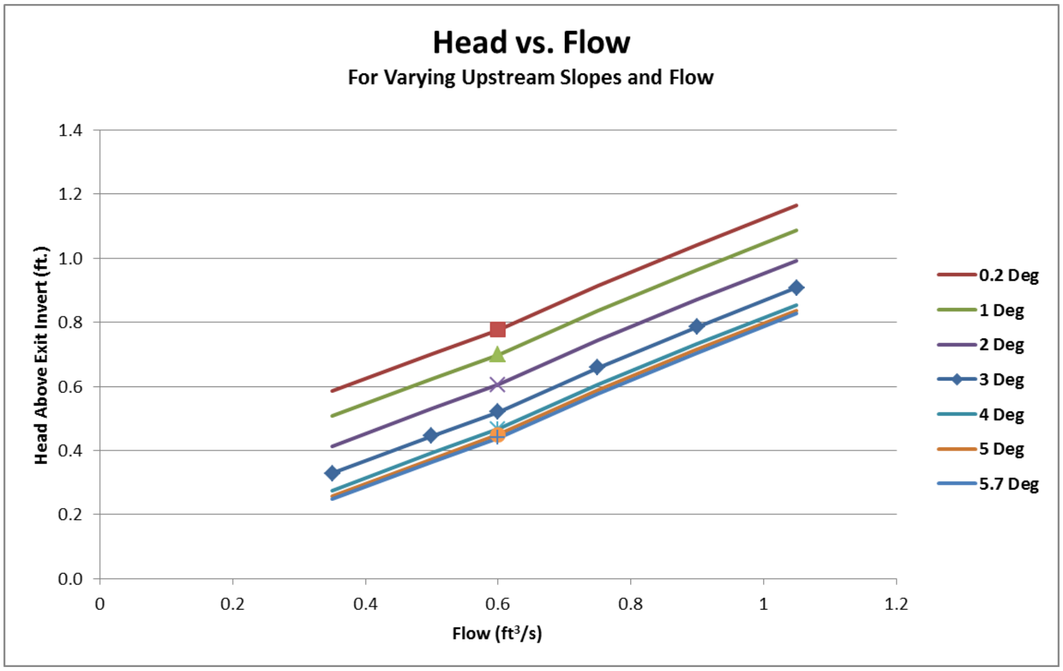

Figure 14. Extrapolated Rating curves, Head vs. Flow for varying slopes.

Physical Model vs. Numerical Model

During physical model testing, a three dimensional computational fluid dynamic (CFD) numerical model was built and tested to evaluate if CFD modeling could replicate the complex hydraulics represented by an articulated fishway. The FLOW-3D numerical model had the same dimensions as the physical model to make comparison easy. The CFD model was set up to match one physical model setup with a constant slope of 3 degrees, a discharge of 0.9 ft^3/s, and no dog ears.

Velocity flow patterns in the CFD model closely resembled the physical model (Figure 15), including recirculation in the pools. Figure 16 shows the WSE measured in the physical model in each pool of the fishway compared to the calculated values in the CFD numerical model. In the physical model only one WSE was measured per pool. In the CFD, the WSE was calculated at each cell in the pool. Areas in Figure 16 without a CFD WSE indicate where the solid fishway baffles are located. These comparisons show that hydraulics in the physical model and CFD model correlate very well.

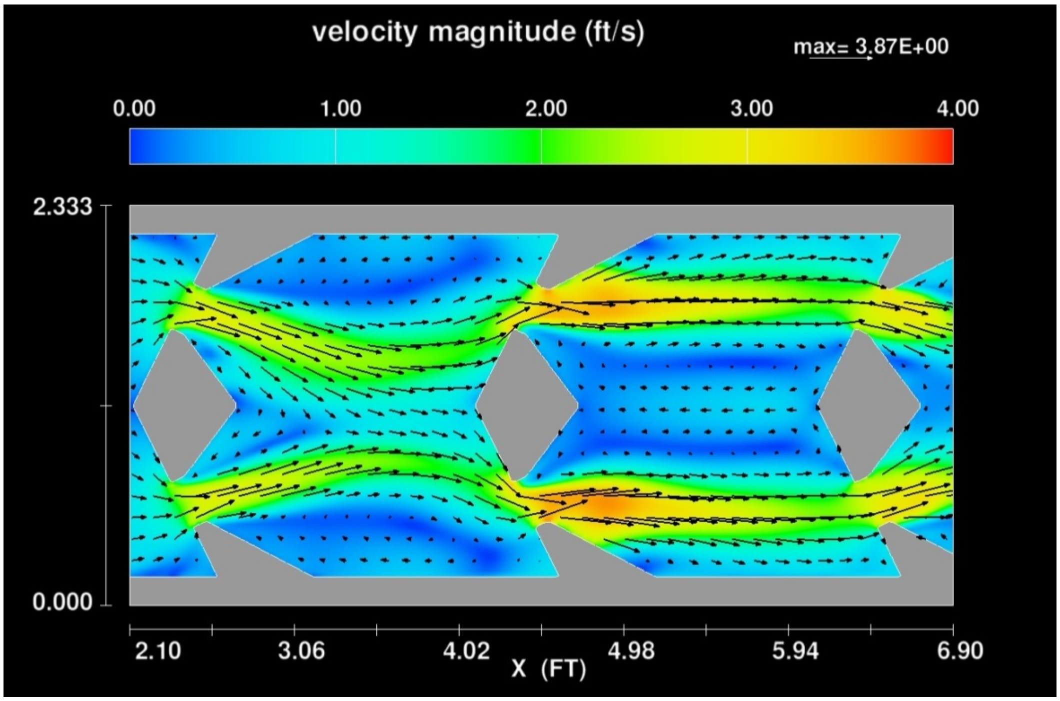

Figure 15 - Velocity flow patterns seen in the CFD model.

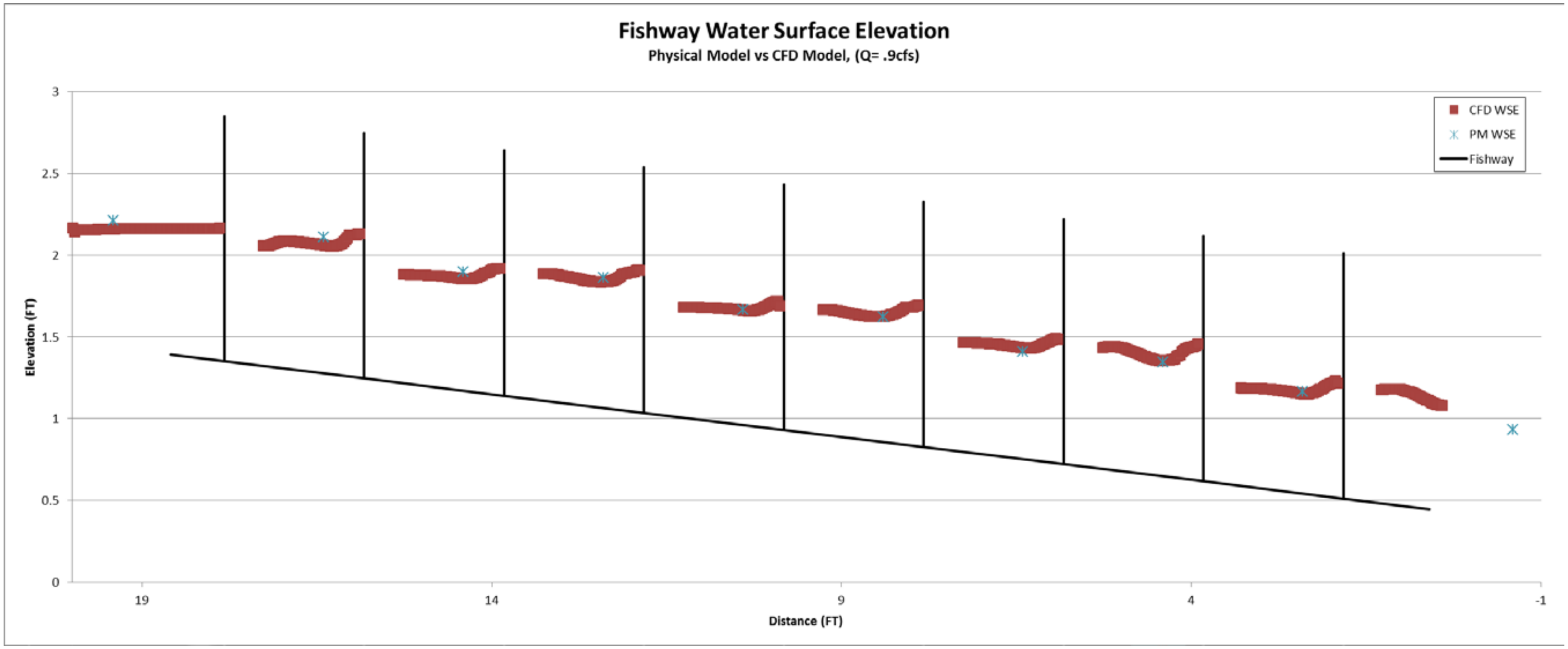

Figure 16. Water surface elevation measurements in each pool of the fishway in the physical model (PM) vs. CFD.

For feasibility and evaluation purposes, the physical and CFD model build and run times were compared. It took approximately 30 staff days to build the physical model and each flow condition took 20 minutes to setup, run, and collect data. The CFD model took approximately 2 staff days to build by an experienced modeler and approximately 4 hours to run one flow configuration. This was a conceptual level CFD model. It should be noted that the CFD simulation was not put through any grid resolution or uncertainty routines which are commonly done to ensure the model represents the flow adequately. Doing these types of routines typically adds several staff days to a CFD study. It is anticipated that each additional CFD configuration would take 2 hours to set up and 4 hours to run.

Self-Regulating Fishway

Forces acting on the fishway

A typical installation of this fishway will be on low head dams with a RWS that fluctuates by less than 3 ft. This type of a fishway will only be successful if it can self-regulate as the RWS changes. The goal is that the self-regulating fishway will adjust to changing RWS in order to maintain a more consistent flow through the fishway regardless of the RWS.

For a constant flow rate: when the fishway is at a low slope the depth of water in the fishway is large. When the fishway is at a steep slope the depth of water is small. In the model study a flow rate of 0.6 ft^3/s was chosen as the target flow rate. At a 0 degree slope the required head is 0.78 ft. At a 6 degree slope the required head is 0.44 ft (see Figure 14).

The upstream end of the fishway is rotating about the hinge. When the upstream end of the fishway is at a low slope the buoyancy force is small; inversely, at a steep slope the buoyancy force is large. Figure 17 and Figure 18 illustrate the fishway at a 0 degree and 6 degree slope (respectively). Each figure illustrates a flow of 0.6 ft^3/s and the required RWS and the pool WSE in the fish way. The amount of buoyant force acting on the fishway is the difference between the pool WSE in the fishway and the RWS. At the low RWS the fishway pool WSE elevations are nearly equal to the RWS (see Figure 17). At the high RWS the fishway pool WSE elevations are significantly lower than the RWS.

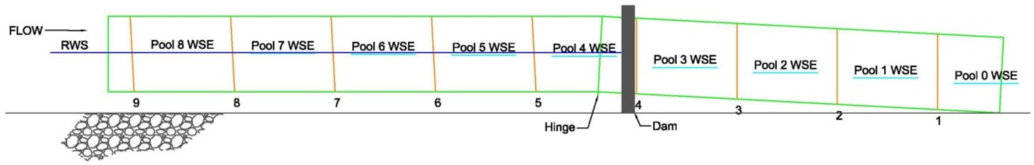

Figure 17. Diagram of the fishway at low RWS, consequently the slope of the upstream half of the fishway is 0 degrees. To obtain 0.6 ft^3/s in the model fishway the depth of flow at the upstream end of the fishway was 0.78 ft. Note the in the upstream half of the fishway the RWS and pool WSE are nearly equal.

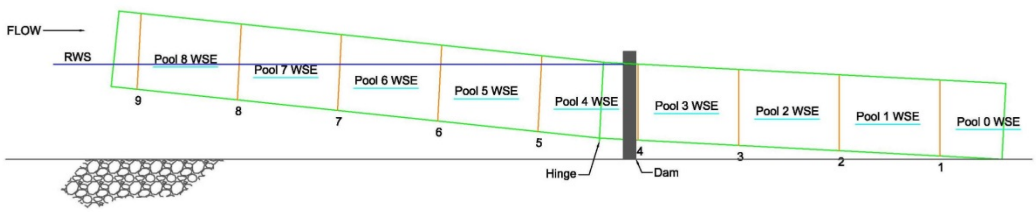

Figure 18. Diagram of the fishway at high RWS, consequently the slope of the upstream half of the fishway is 6 degrees. To obtain 0.6 ft^3/s in the model fishway the depth of flow at the upstream end of the fishway was 0.44 ft. Note the in the upstream half of the fishway the RWS is significantly higher than the pool WSE.

Consequently the resulting force required to hold the fishway at the correct elevation varies greatly over the range of slopes tested. At a low RWS condition shown in Figure 17 the force required to hold the fishway in that position is 218 lbs in the up direction. At a high RWS condition shown in Figure 18 the force required to hold the fish way in that position is 4 lbs in the down direction. During the initial laboratory test a chain hoist was used to adjust the upstream slope (see Figure 19). The 2-foot wide by 9.5-foot long upstream half of the laboratory model weighed approximately 400 lbs. During testing with steep slopes extra weight had to be added to the fishway to keep it from floating.

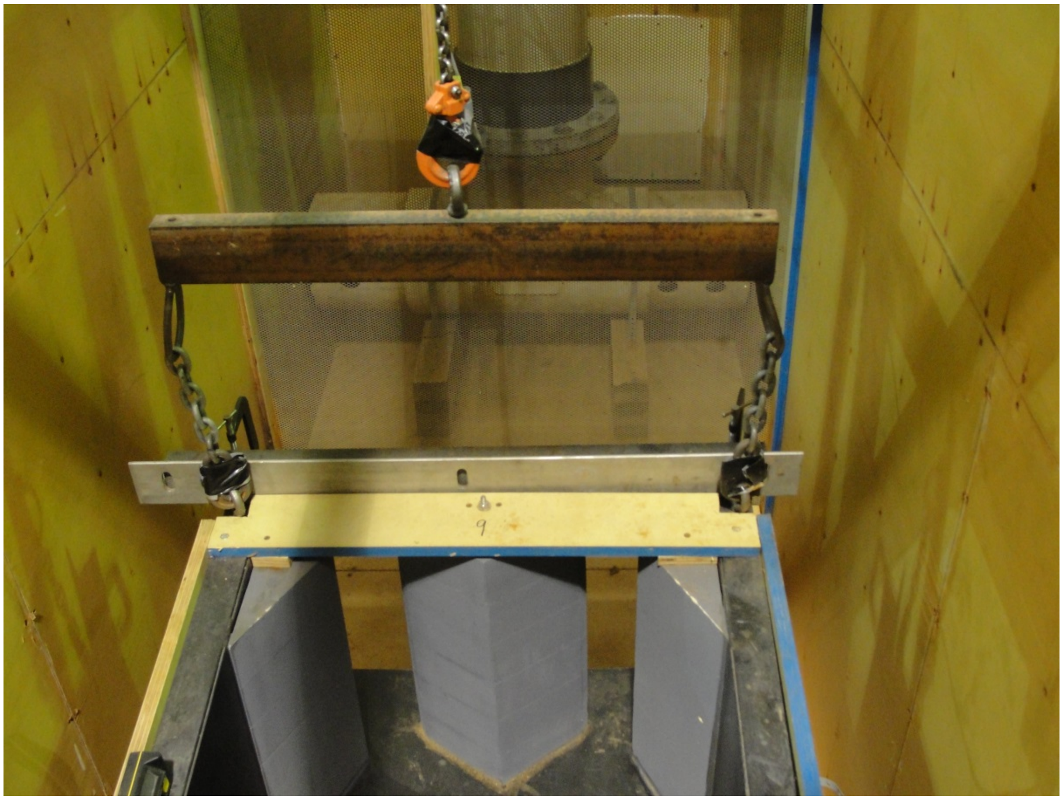

Figure 19. Laboratory setup with a chain hoist being used to adjust the upstream half of the fishway.

Float Method

During phase one in the laboratory small floats were added to the fishway in an attempt to self-regulate the upstream fishway elevation. The fishway would not stabilize at a specific elevation, but would either sink or float. Once the fishway started to float, the buoyancy would increase and it would rise to the surface quickly. The inverse is true as it started to sink. Given the initial fishway setup location in the laboratory it was not possible to attach large enough floats to control ascent or decent. Phase two of this study moved to test fishway to a different location with a large reservoir where large barrels could be added to sides of the fishway (see Figure 20). The test rig allowed two barrels to be moved up, down and placed at an angle.

Figure 20. Model fishway with 30-gallon barrels attached to each side. With the barrels in this position the fishway did not have a nearly constant flow rate for varying RWS elevations.

As described in the previous section; the buoyant forces change dramatically when the fishway is at different slopes. With the barrels mounted on the side of the fishway the buoyant forces provided by the barrels changes depending on the submergence of the barrels. The barrels needed to be positioned such that at a low RWS they provided a large amount of buoyant force and at a high RWS they provided little or no buoyant force. At very high RWS elevations the weight of the barrels was required to overcome the buoyancy of the fishway. It was difficult to get the barrels in the exact perfect positions so that the fishway would function properly and pass a nearly constant flow at varying RWS elevations.

Initially the barrels were placed on the sides of the fishway near the upstream end. The fronts of the barrels were at the front of the fishway. Different configurations of barrel elevation (in relation to the fishway), barrel angle and size of barrels (30 gallon and 50 gallon) were evaluated. The barrels could be positioned such that they would float the fishway however obtaining a constant flow for varying RWS was not achieved until the barrels were moved to out in front of the fishway. The barrels were placed so the downstream end of the barrels was almost equal to the upstream end of the fishway (see Figure 21 and Figure 22). Then the barrel elevation and angle was appropriately adjusted to allow the fishway to pass a nearly constant flow for varying RSW elevations.

Figure 21. Fishway self-regulating by float method.

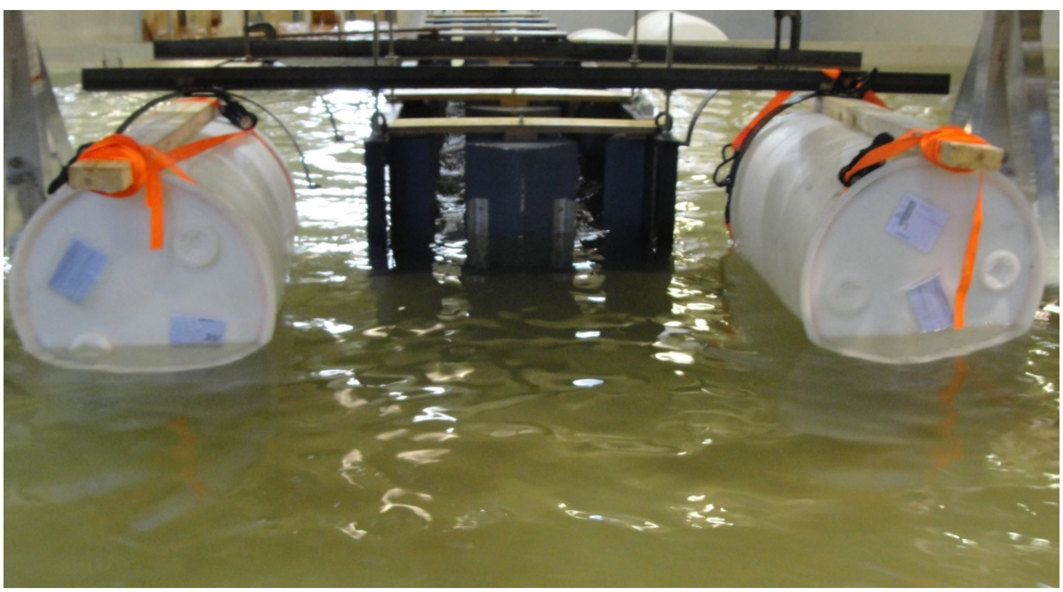

Figure 22. Fishway self-regulating by float method. Note the barrels are extending in front of the fishway.

In this configuration the fishway responded well to changes in the RWS. Tabular data of the RWS, slope and calculated flow in the fishway are shown in Table 1.

The calculated flow in the fishway was close to a constant flow rate. Further adjustment of the barrels may be able to dial in the desired flow to achieve more consistency.

Table 1. Tabular Data of the Self-Regulating fishway by Float Method

Run #	Slope	Head	RWS	Calculated Q
	Degrees	Ft	Ft	Ft^3/s
34	0.9	0.76	1.77	0.65
33	2	0.73	1.91	0.73
32	3.6	0.65	2.10	0.78
35	4.7	0.59	2.25	0.75
31	5.9	0.51	2.35	0.69

Precise location of the barrels can be calculated however final adjustment to barrel positon will need to be completed in a field setting. In the laboratory this was made easier because of the ability to remove water from the test area and the ability to manually adjust the RWS. Field setup of barrels will likely be difficult due to the inability to manually adjust the RWS and the "in water" work. This method of self-regulation is simple and does not require the use of electronics or an additional support structure in the reservoir.

Water Level Sensor, PLC, and Electric Hoist Method

The second method used to achieve self-regulation is a water level sensor that is attached to a Programmable Logic Controller (PLC) and an automatic hoist. The water level sensor measured the changes in RWS and directed the hoist to adjust the upstream end of the fishway accordingly to maintain a constant flow.

A Global Water pressure transducer with a range of 0 to 3 ft was positioned in the reservoir and connected to a Control Design CD 100 PLC. A Venture Maxi 24-inch linear actuator connected the upstream end of the fishway to a support framework above the reservoir (see Figure 23). The PLC controlled the operation of the linear actuator (see Figure 24). The PLC and actuator were powered by a 12 volt battery.

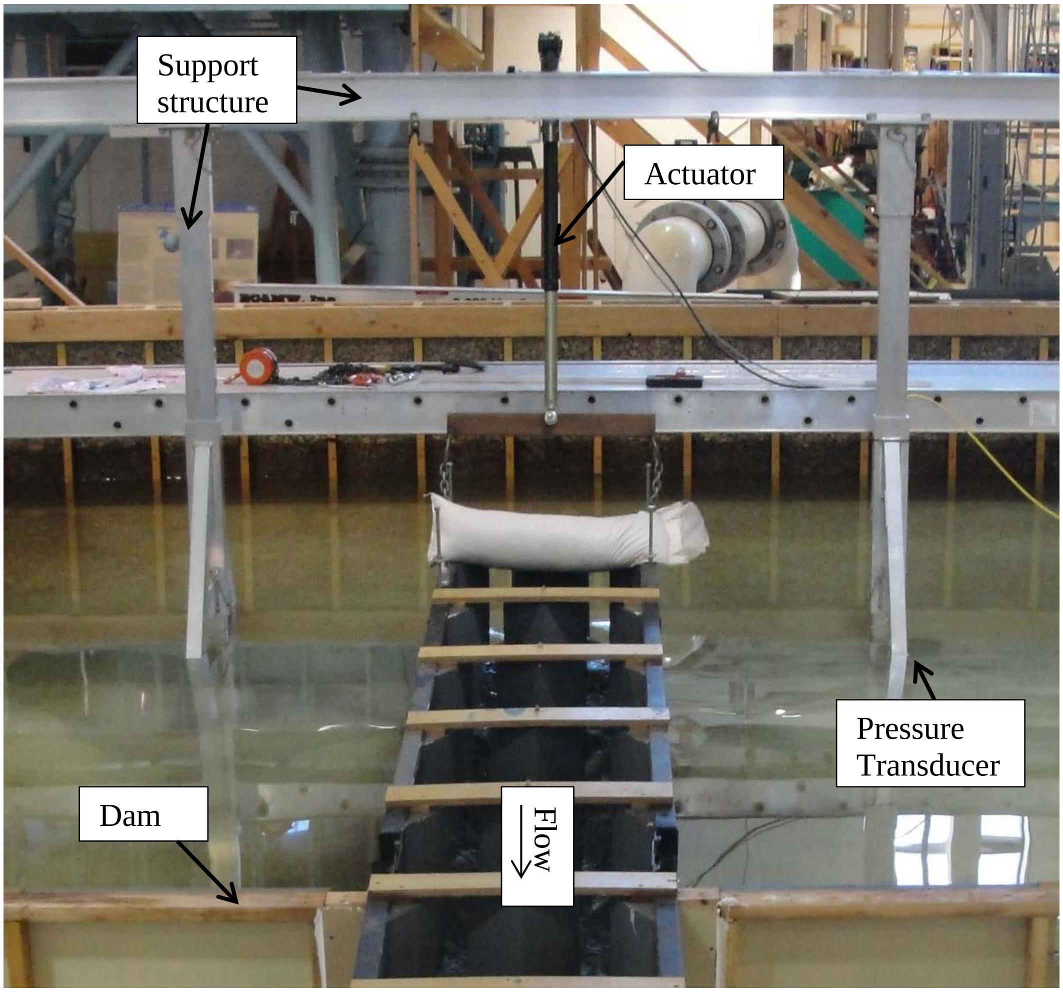

Figure 23. Fishway setup with Pressure Transducer, PLC and linear actuator used to self-regulate to varying RWS.

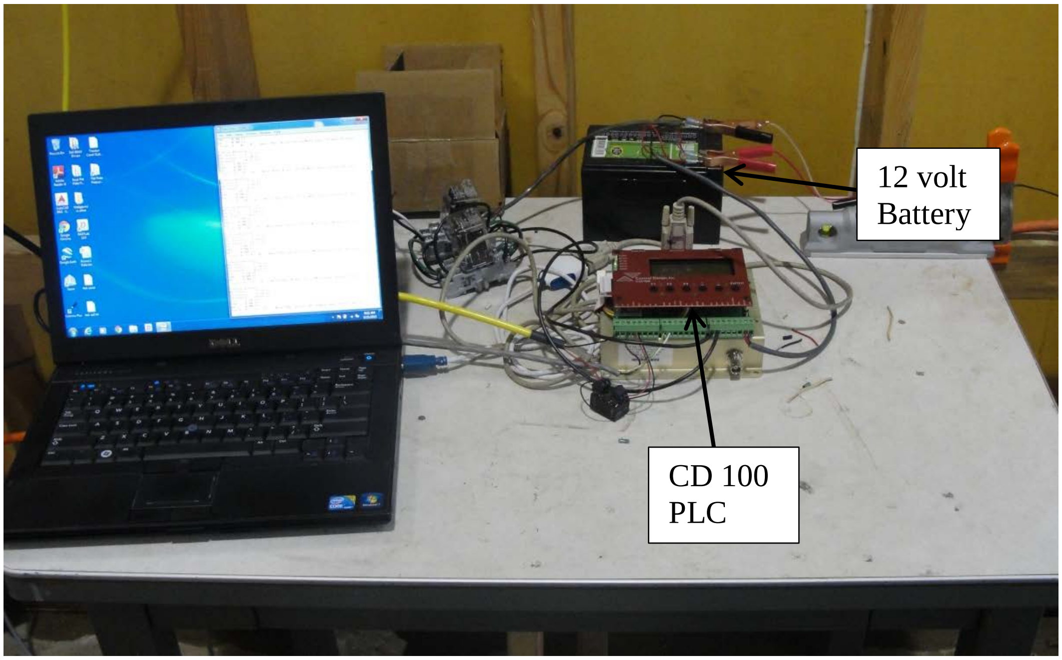

Figure 24. PLC setup used to control the linear actuator.

For the design flow of 0.6 ft^3/s, the relationship (see Figure 25) between the RWS and the upstream invert of the fishway was developed from the rating curve data shown in Figure 14. A second degree polynomial equation was curve fit to the data and programed into the PLC. The PLC reads the RWS pressure transducer once a minute and calculates the target elevation of the fishway invert. If the absolute value of the difference between the actual invert and the target invert is greater than 0.02 ft the PLC directs the linear actuator to adjust to the target invert.

In this configuration the fishway responded very well to changes in the RWS. Tabular data of the RWS, slope and calculated flow in the fishway are shown in Table 2 . The calculated flow in the fishway was very close to the target constant flow rate.

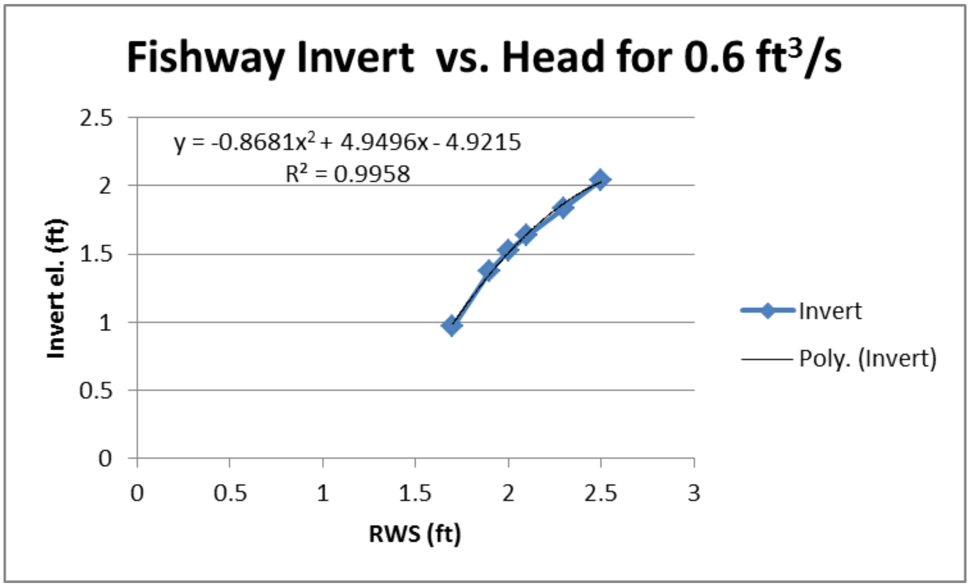

Figure 25. Relationship between RWS and fishway invert for a constant flow of 0.6 ft^3/s.

Table 2. Tabular Data of the Self-Regulating fishway by PLC method

Run #	Slope	Head	RWS	Calculated Q
40	1.6	0.64	1.76	0.60
39	2.6	0.57	1.84	0.61
38	3.1	0.55	1.91	0.63
37	4.9	0.48	2.15	0.62
36	6.3	0.44	2.36	0.61

This setup took two 2 people a day to set up the water level sensor, PLC, and actuator. A field setup would also include a solar panel to charge the 12 volt battery and a protective enclosure to house the electronics. A typical field enclosure is shown in Figure 26 and Figure 27. An equation to relate RWS and fishway invert for a design target flow rate would also have to be calculated. This method of self-regulation also includes a support structure built over the fishway to support the lifting of the fishway. The electronics involved to control fishway cost about $2,000 (2015 value).

Figure 26. Typical field electronic enclosure with solar panel.

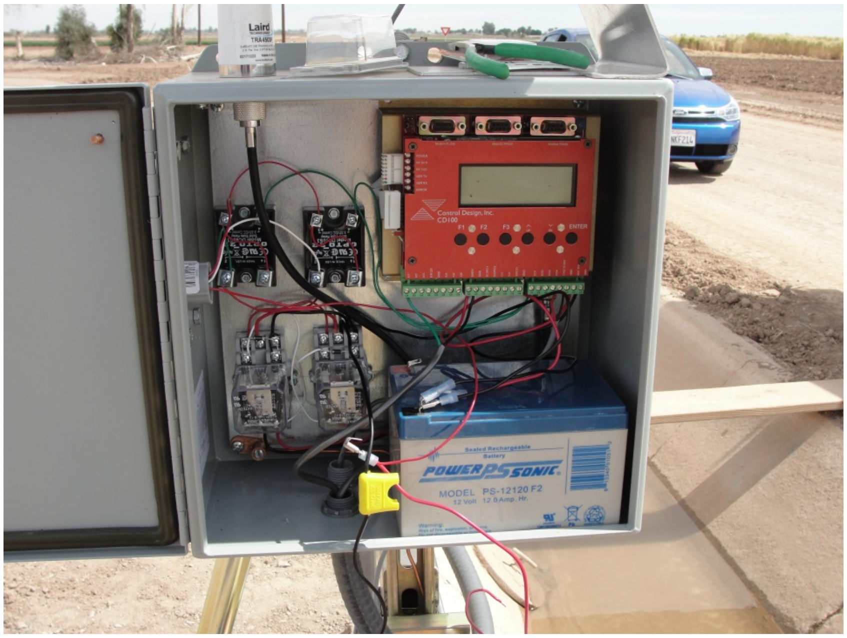

Figure 27. Typical field electronic enclosure showing PLC, Battery and electrical relays.

Conclusions

- The duel vertical slot fishway is ideal for this application as it can operate well for varying pool depths.

- The duel vertical slot fishway requires the use of dog ears to produce uniform flow conditions through the fishway.

- Throughout the range of slopes and flow rates tested, there were no adverse hydraulic conditions that would hinder fish passage caused by a duel vertical slot fishway with 2 slopes.

- The fishway should be designed so that the maximum pool drop and slot velocity does not exceed the target species design criteria.

- CFD modeling of the fishway accurately represented the hydraulic flow patterns, WSEs, and velocities in the physical model.

- Self-regulation of the fishway can be accomplished by either the float method or with a water level sensor, PLC, and electric hoist system. Both methods of self-regulation tested would eliminate the need to manually adjust the fishway and would operate successfully with minimal operator assistance.

- The float method field setup will likely be difficult due to the inability to manually adjust the RWS and the "in water" work. However, this method of self-regulation is simple and does not require the use of electronics or an additional support structure in the reservoir.

- The water level sensor, PLC, and electric hoist method of self-regulation will be simpler to automate in the field than the float method. However, it also requires electronics and a structure built in the reservoir over the fishway to support the lifting of the fishway.

- The upstream section of the test fishway was 9.5 ft long. In order to provide biological acceptable operation of the fishway a maximum range in RWS was approximately 0.7 ft. This range could be extended by increasing the length of the upstream section. However, the depth of the fishway would also have to increase.