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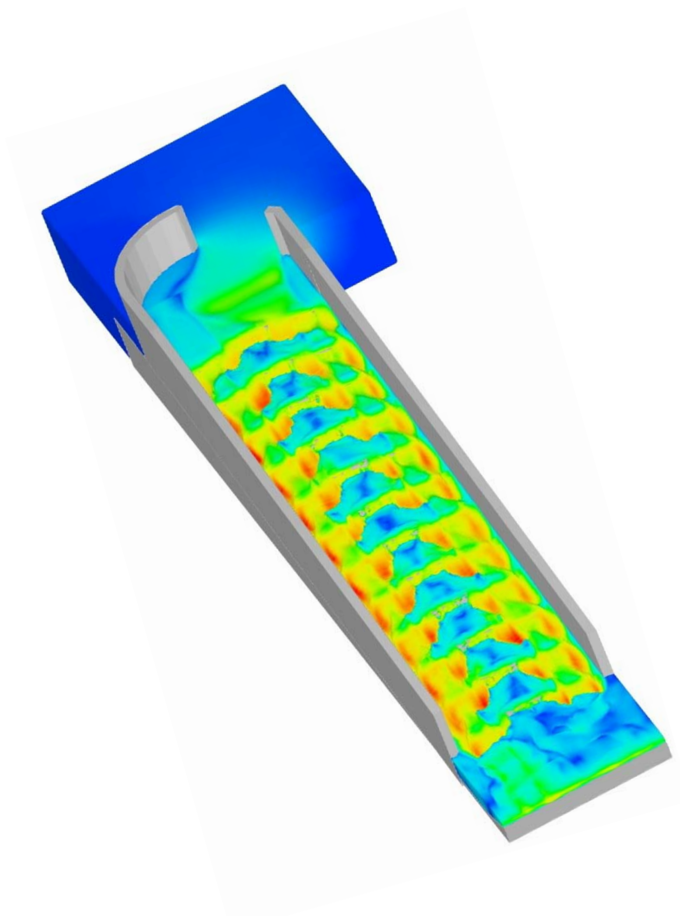
Hydraulic Laboratory Report HL-2011-04

Robles Diversion Dam - Left Bank Fishway

High Flow Bypass Spillway Structure
Ventura River, California



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Services Group
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This report presents the results of a Bureau of Reclamation study to develop the design of a fishway providing passage during operation of the proposed high-flow bypass (HFB) spillway at Robles Diversion Dam. The HFB spillway and fishway are designed as auxiliary facilities that will only operate during floods in excess of about the two-year event. The primary species of concern requiring passage is southern California steelhead, (*Oncorhynhus mykiss*). The fishway design was developed through a combination of three dimensional computational fluid dynamics (CFD) modeling and a 1:10 Froude-scale physical model. The study focused on development and evaluation of a fishway design providing effective fish passage during flood events that convey significant debris and sediment.

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Ventura River, California

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

Acknowledgments

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Hydraulic Laboratory Reports

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Executive Summary

This report presents the results of a Bureau of Reclamation study to develop the design of a fishway providing passage during operation of the proposed high-flow bypass (HFB) spillway at Robles Diversion Dam. Robles Diversion Dam is located in southern California on the Ventura River approximately 14 river miles from the ocean and approximately two miles downstream of Matilija Dam. The HFB spillway and fishway are designed as auxiliary facilities that will only operate during floods in excess of about the two-year event. The primary species of concern requiring passage is southern California steelhead, (*Oncorhynhus mykiss*). The fishway design was developed through a combination of three dimensional computational fluid dynamics (CFD) modeling and a 1:10 Froude-scale physical model. The study focused on development and evaluation of a fishway design providing effective fish passage during flood events that convey significant debris and sediment. Fishway designs were tested to investigate flow conditions in the fishway, determine fishway discharge rating and evaluate debris passage characteristics of the design. A preferred baffle design was developed for the fishway based on the study. All dimensions presented in the study are in English units.

Background

Robles Diversion Dam is located on the Ventura River near Ventura, California at approximately river mile (RM) 14.16 (Figure 1). The diversion supplies water to Lake Casitas by canal. The normal maximum diversion is approximately 500 ft^3/s. The existing diversion dam is a low rock weir with a gated spillway, canal diversion headworks and a fish pass located on the right abutment. The diversion weir has a hydraulic height of 13 feet.

Figure 1 – Aerial view of Robles Diversion Dam.

Two miles upstream of Robles Diversion Dam is Matilija Dam, a 160 ft high (originally 190 ft high) concrete arch dam that is scheduled to be removed to restore access to the upper watershed for southern California steelhead (*Oncorhynhus mykiss*). Removal will release large volumes of sediments to the lower river impacting operation of Robles Diversion Dam. Mitigation of impacts prompted the design of a new auxiliary spillway at Robles Diversion Dam designed specifically to pass large flood flows and sediment loads through the dam. The new auxiliary spillway at Robles, referred to as the high-flow bypass (HFB) spillway, will be located to the left of the existing spillway. The spillway was the focus of a model study in 2008, (Mefford et. al. 2008). During the 2008 study, concerns were raised over the adequacy of the existing right bank fishway to attract upstream migrating fish during HFB releases. These concerns resulted in a second study to investigate the design of a left bank auxiliary fishway designed to operate in conjunction with the HFB spillway. The 2008 study recommended a HFB fishway be located adjacent to the left spillway abutment as shown in Figure 2.

This report covers physical and numerical modeling of the fishway conducted at the Bureau of Reclamation's Hydraulics Laboratory in Denver, Colorado. The model study provided design support to the Army Corps of Engineers, Los Angles District, the principle designer for the project.

Study Objectives

The primary objectives of the model study were to develop a fishway design based on the following performance objectives:

1. Fishway flow conditions shall encourage upstream passage of adult steelhead. Steelhead are strong swimmers. Several researchers have reported swimming speeds and recommended velocities for upstream passage of adult steelhead trout (McEwan 2001, Bell, 1991, Bjornn and Reiser, 1991 reported in Levy and Slaney, 1993). McEwan suggests passage should not require fish to exceed swimming at 10.0 ft/sec for more than 5 seconds while Bell; and Bjornn and Reiser suggest steelhead are capable of sustained swim speeds in access of 10 ft/s and darting speeds in excess of 15 ft/s. Thompson, 1972 (reported in Barnhart, 1986) reported upstream migration of steelhead is not impaired at depths greater than 0.6 ft, however, deeper depths are recommended for passage. Based on the cited studies, a flow velocity objective for the HFB fishway of 10 ft/s with frequent resting pools was adopted. The objectives for fishway flow depth were set as follows; pool depth = 3 to 4 ft and passage depth = 1.0 to 3 ft.
2. The fishway will only be operated during flow releases through the HFB spillway. The fishway may operate several times a year for a typical duration of one day to five days.
3. Due to anticipated high debris loads during operation, auxiliary attraction flow requiring a grated intake is not acceptable. Attraction to the fishway entrance is to be achieved by flow conveyed through the fishway channel.
4. Fishway flow will likely contain high amounts of brush, willows and other types of small woody debris dislodged during strong storm events. To the degree possible, fishway operation should not be impaired by debris entrained with fishway flow. As a flood-only-operated fishway, the fishway will draw water from high in the diversion pool at all times, thus primarily entraining floating debris.

5. The fishway entrance must be located within the HFB stilling basin pool thus allowing fish within the HFB spillway stilling basin to access the fishway.
6. Stranding of fish within the fishway is a concern during fishway shutdown. Minimizing the opportunity for fish stranding requires controlling flows during facility shutdown. The fishway should provide for a gradual reduction in fishway flows combined with a gradual concentration of flow during shutdown. Fish accustom to the rapid decline of flows that occur in desert streams will likely respond to declining flow and flow depth signals by moving out of the fishway either upstream or returning downstream to the stilling basin pool. Water and fish in the stilling basin pool following closure of the HFB spillway will be passed into the river channel immediately downstream of the service spillway where upstream passage can occur through the existing fishway (Mefford et. al., 2008).
7. The fishway exit shall be gated to prevent flow entering the fishway during non- HFB spillway operation. The release of any flow (including gate leakage) thought the left bank fishway during non-HFB spillway operation is highly undesirable due to the value of the water.

Study Approach

The 2008 HFB spillway study produced a preliminary fishway design based on a hydraulic drop of 12.3 ft and a fishway length of about 150 feet or a fishway slope of about eight percent. The present study evaluated the preliminary fishway design against fishway performance objectives and implemented a series of modifications to the design to improve fishway performance. The fishway study objectives supported the development of a HFB fishway with similar characteristics to many roughened channel style fishways successfully used by Reclamation at slopes of generally less than five percent, Mefford, 2009. Two principle characteristics of many Reclamation roughened channel fishways desirable in the Robles HFB fishway are:

- A wide trapezoidal channel designed to pass large flows through the fishway, thus avoiding the need for auxiliary attraction flow. The trapezoid channel provides diversity of flow depth and velocity within the channel cross section.

- Multiple slot baffles designed to pass floating debris. Flow baffles are composed of a series of concrete piles or rock boulders placed across the fishway. Baffle segments referred to as piles are designed to be submerged during large flow events. Overtopping a segment of the baffles promotes debris passage and produces a rapid increase in fishway flow at the onset of overtopping enhancing fish attraction as river stage rises.

The study is designed to investigate the hydraulic characteristics of minimally baffled fishways at a slope of about 8 percent. The unique operating requirements of the Robles HFB fishway resulted in a study implementing both three dimensional numerical modeling and a physical model.

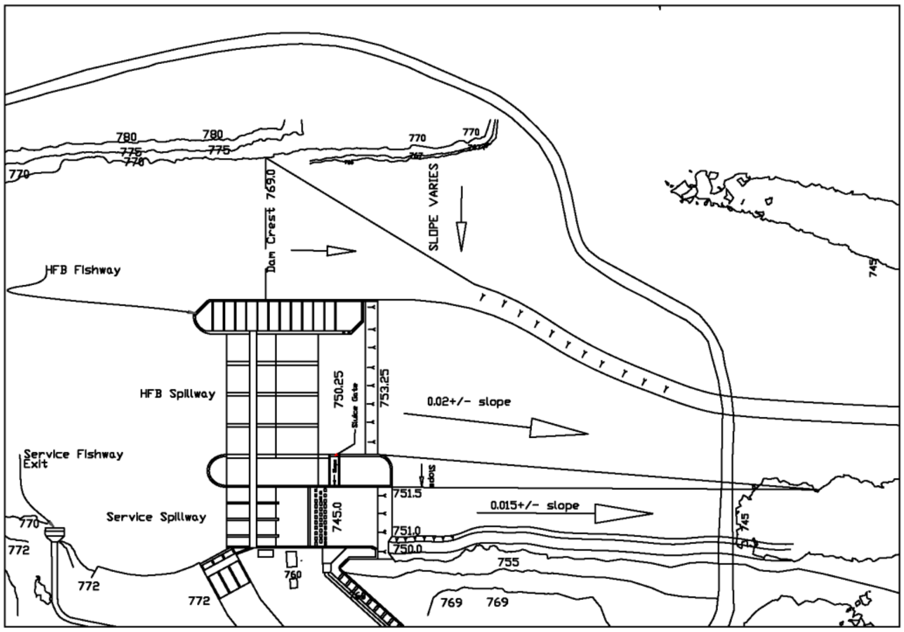


Figure 2 – Plan view of proposed HFB spillway and new HFB fishway, (Mefford et.al., 2008).

Fishway Baffle Development

3-Dimensional Computational Fluid Dynamics (CFD) Modeling

A three dimensional CFD model of an eight percent slope roughened channel fishway with baffles composed of cylindrical piles was developed to investigate fishway flow conditions. The CFD model included approximately 100 ft of the upstream diversion pool, fishway exit structure, baffles and entrance. Simulations of four baffle designs were conducted (labeled A to D in Figure 3). These models allowed investigators to determine how fishway designs successfully used at lower slopes would operate at an eight percent slope. Cylindrical shaped pile baffles were used for ease of modeling. Piles were arranged in an upstream pointing chevron shape similar to other Reclamation roughened channel fishways.

The chevron baffle pattern is used to concentrate flow toward the center of the fishway channel and provide greater variability of passage flow conditions (Mefford, 2009). To promote flushing of floating debris through the fishway, the height of the three center piles were set lower than piles located to the outside of the channel. A 20 ft wide weir with a crest elevation of 766.0 was modeled across the fishway exit. The weir was proposed during the HFB spillway design to restrict fishway operation to diversion pool elevations above the elevation required for full diversion. The invert elevation of the fishway entrance was set at 750.25, equal to the invert elevation of the stilling basin floor.

A trapezoidal fishway channel 32.0 ft wide at the top with a 8 ft wide bottom and 3H:1V side slopes was modeled for all simulations, Figure 3. The channel invert was assumed to be riprap lined and was represented by a 0.5 ft uniform channel roughness height. All baffle configurations were modeled as groups of piles set in a chevron shape with an internal angle of 150 degrees. Twelve baffles consisting of nine piles each were spaced at 14.6 ft center to center along the fishway. The baffle spacing yields a step-pool style fishway with approximately 1.1 ft water surface drop between pools. All simulations were modeled using a fishway flow of 200 ft^3/s which corresponded to the predicted maximum flow that could be passed over the fishway exit weir at diversion pool elevation 768.0.

Baffle A (see Figure 4) consisted of nine 2-ft diameter piles spaced on 3.5 ft centers with 1.5 ft clear opening between piles. The height of the piles relative to the top of riprap in the center of the channel starting with the center pile and moving outward were 4.0 ft, 4.5 ft, 5.0 ft, 5.0 ft and 5.0 ft, respectively. Fishway surface flow velocities (not depth averaged) from the simulation are shown in Figure 5. Surface velocity between piles located in the center of the channel is 10 ft/s to 12 ft/s. Flow velocity between piles located closer to the channel fringes reduces to about 6 ft/s to 8 ft/s. Pool velocity ranges from about 2 ft/s to 4 ft/s. Corresponding flow depths predicted from the simulation are shown in Figure 6. A fishway flow of 200 ft^3/s resulted in a depth in the center of the channel of about 4.3 ft producing shallow overtopping of the center pile. All piles located off centerline extended above the flow. Flow conditions within the fishway at 200 ft^3/s were considered acceptable for passage of adult steelhead however, submergence of the center piles was felt to be insufficient to achieve flushing of floating debris through the fishway.

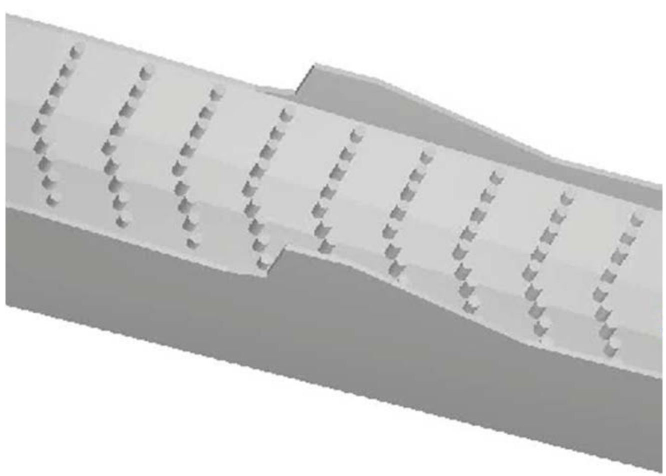


Figure 3 – Isometric view showing a section of the trapezoidal fishway channel with cylindrical pile baffles modeled in Flow3D.

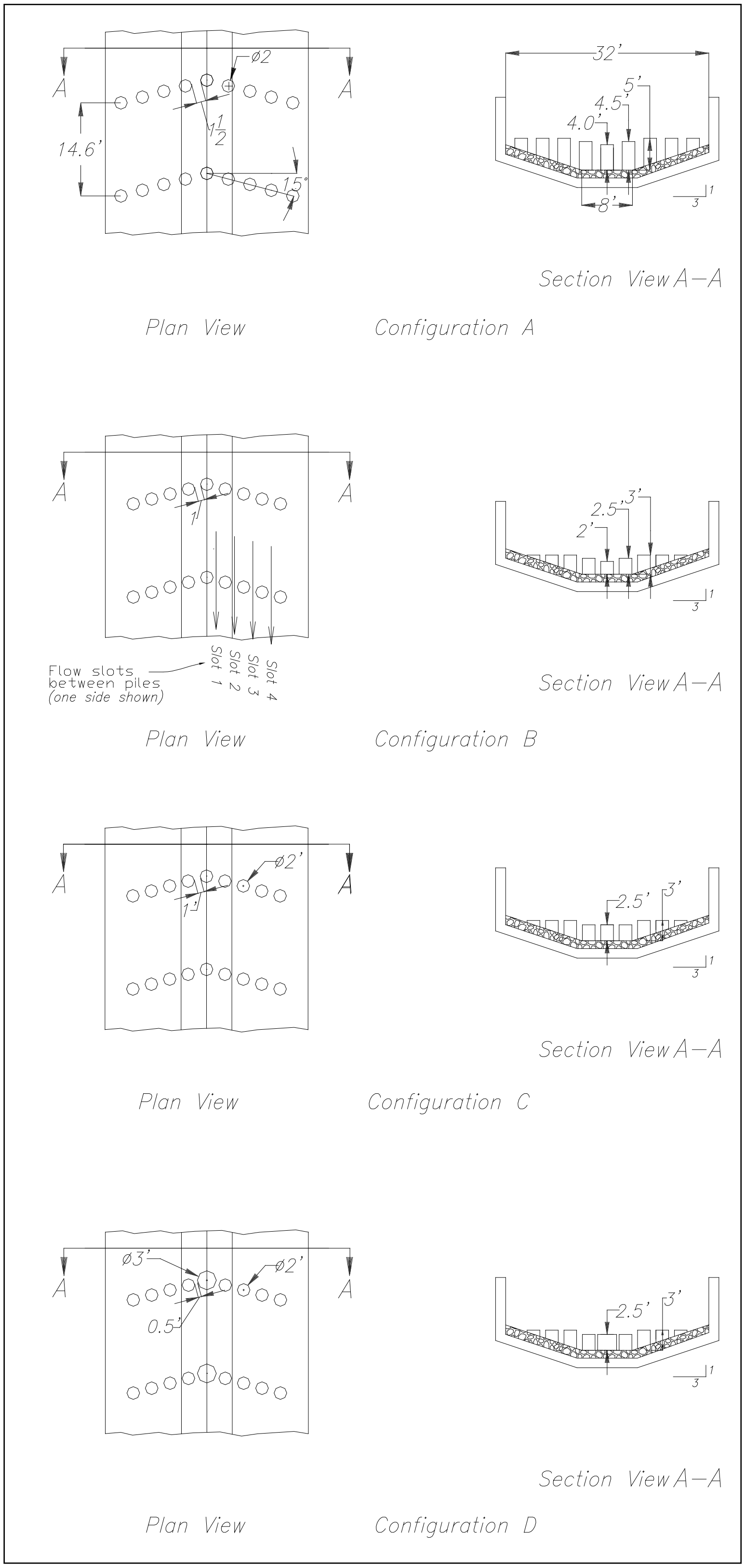


Figure 4 – Fishway baffle designs modeled using the numerical model Flow3D.

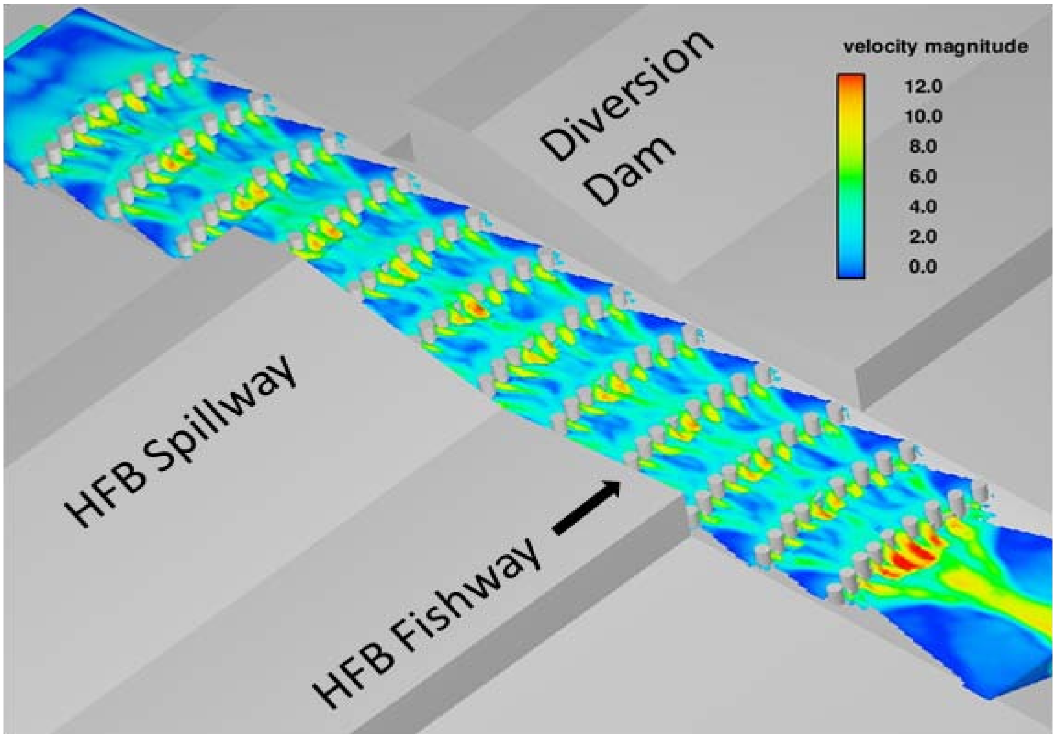


Figure 5 – Isometric view of fishway showing surface flow velocity in ft/s for Baffle A at 200 ft^3/s.

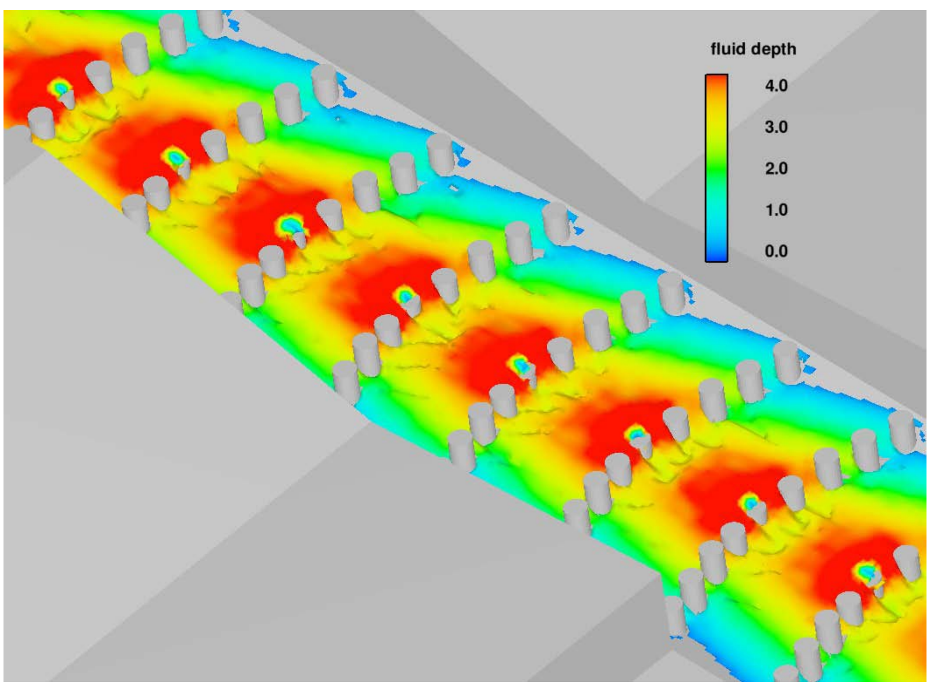


Figure 6 - Fishway flow depth in feet at 200 ft^3/s flow for Baffle A.

A second simulation was conducted of a modified baffle with shorter piles designed to increase the amount of unobstructed near-surface flow in the center of the fishway. Baffle B (see Figure 4) consisted of nine 2.5-ft-diameter piles spaced on 3.0 ft centers with a 1.0 ft clear opening between piles. The spacing between piles was decreased to maintain approximately a 4 ft flow depth in the fishway. The height of the piles relative to the top of riprap in the center of the channel starting with the center pile and moving outward were 2.0 ft, 2.5 ft, 3.0 ft, 3.0 ft and 3.0 ft, respectively. Figures 7 shows fishway surface flow velocity for Baffle B. A strong centered flow is evident with velocity reaching 14 ft/s downstream of the center piles and generally less than 10 ft/s to either side. Vertical velocity contours cut along the fishway passing between piles (see Figure 7 are given in Figures 8, 9 and 10. Figure 8 shows flow velocity and depth along slot line 1 shown in Figure 7. Flow is dominated by standing waves formed by the baffles followed by deep toughs in the pool area between baffles. Flow velocities generally exceed 10 ft/s in the toughs between waves. A similar plot along slot line 2 (Figure 9) shows less wave action and generally lower velocity. Flow velocity along the second slot line is about 8 ft/s to 10 ft/s through the slots with pool velocities less than about 6 ft/s. Closer to the bank, flow velocity and depth decrease further as shown in Figure 10. A plan view showing flow depth at a flow of 200 ft^3/s is given in Figure 11. The center three piles are overtopped by about 1 ft by the standing waves atop each baffle. The scalloped depth pattern in the center of the channel shows the extent of the strong wave action noted.

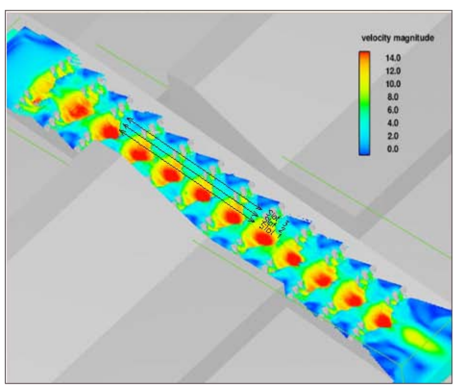


Figure 7 - Surface flow velocity in ft/s for Baffle B at 200 ft^3/s fishway flow.

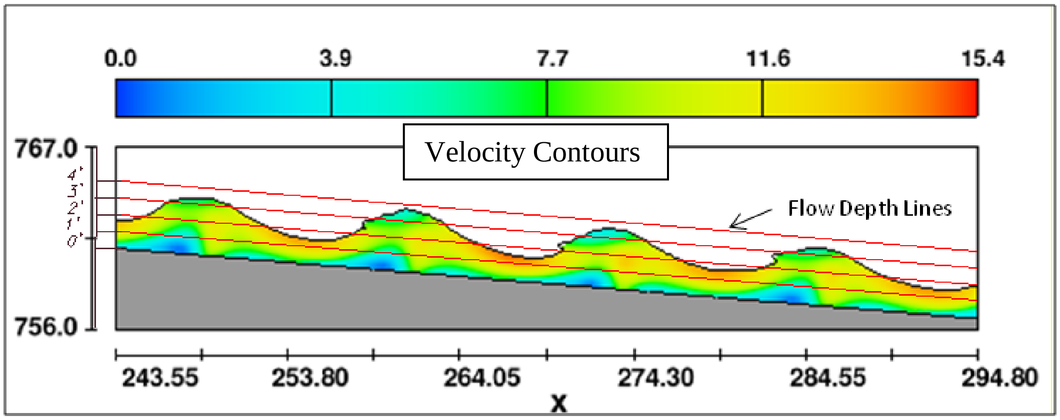


Figure 8 - Baffle B, XZ Section cut through slot 1, see Figure 7.

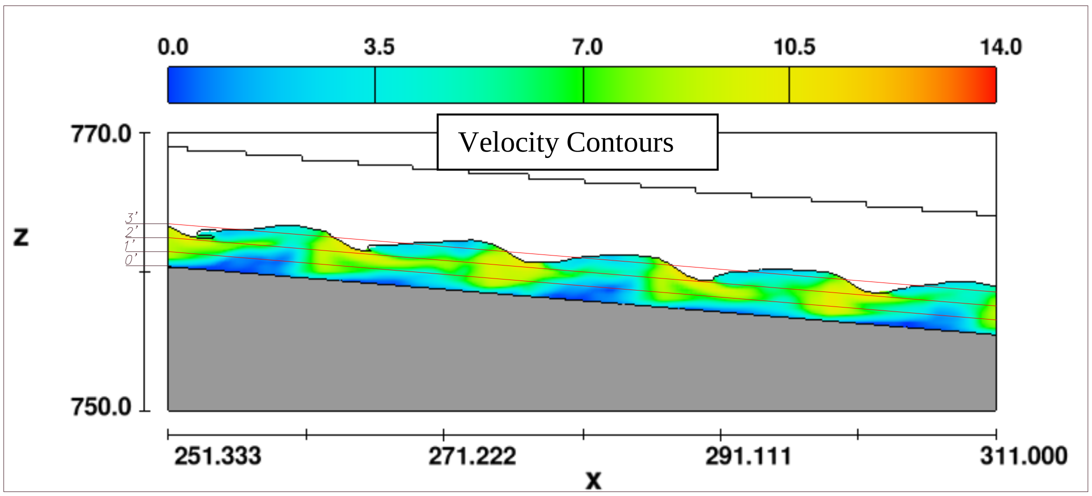


Figure 9 - Baffle B, XZ Section cut through slot 2, see Figure 7.

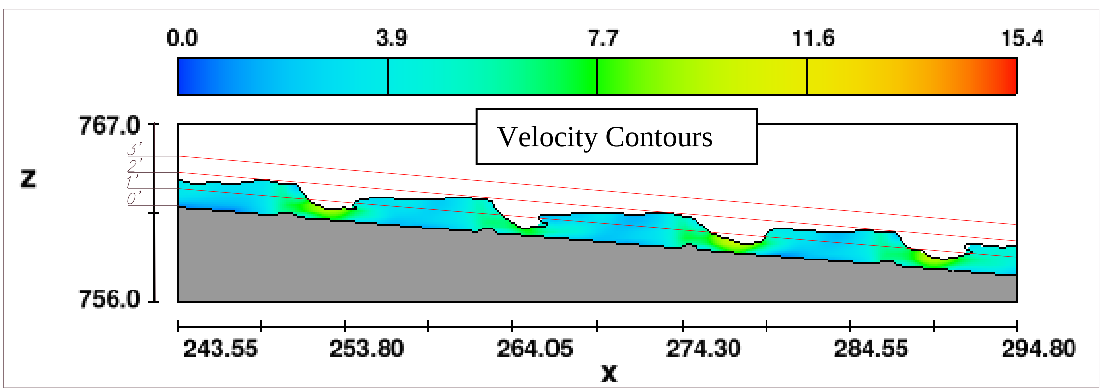


Figure 10 - Baffle B, XZ Section cut through slot 3, see Figure 7.

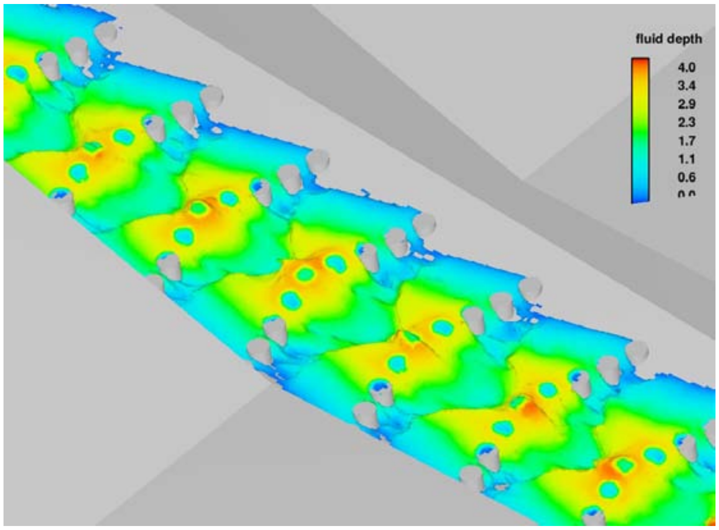


Figure 11 - Fishway flow depth (ft) at 200 ft^3/s flow for Baffle B.

A third simulation was conducted of the fishway with the baffle center pile raised 0.5 ft (see Figure 4, Baffle C). The center pile was raised in an attempt to increase baffle control and dampen the strong wave action noted for Baffle B. A plot of surface velocity is shown in Figure 12. Fishway flow using Baffle C shows a reduction in the highest velocity regions downstream of each baffle compared to Baffle B (Figure 7). This is also shown by comparing vertical sections along slot line 1 in Figures 13 and 8. Comparing flow conditions along adjacent slot lines (Figures 13 and 14), indicate using piles of similar height in the center of the channel yields better uniformity of flow conditions when piles are submerged. Flow depth within the fishway at a flow of 200 ft^3/s is shown in Figure 15. Depth near the center of the fishway is about 3.5 ft. Flow overtops the center three piles from 1.0 ft to 1.3 feet.

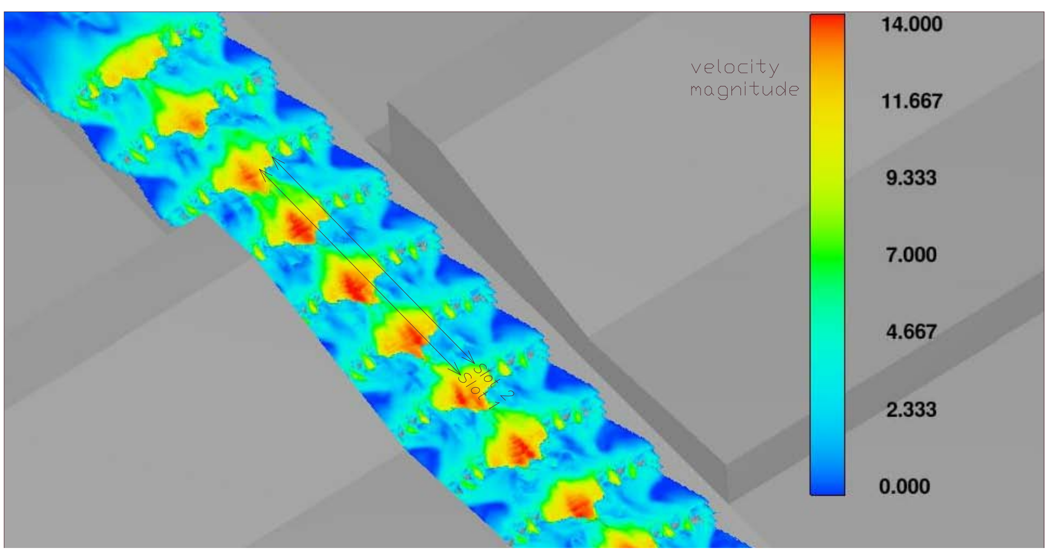


Figure 12 - Surface flow velocity in ft/s for Baffle C at 200 ft^3/s fishway flow.

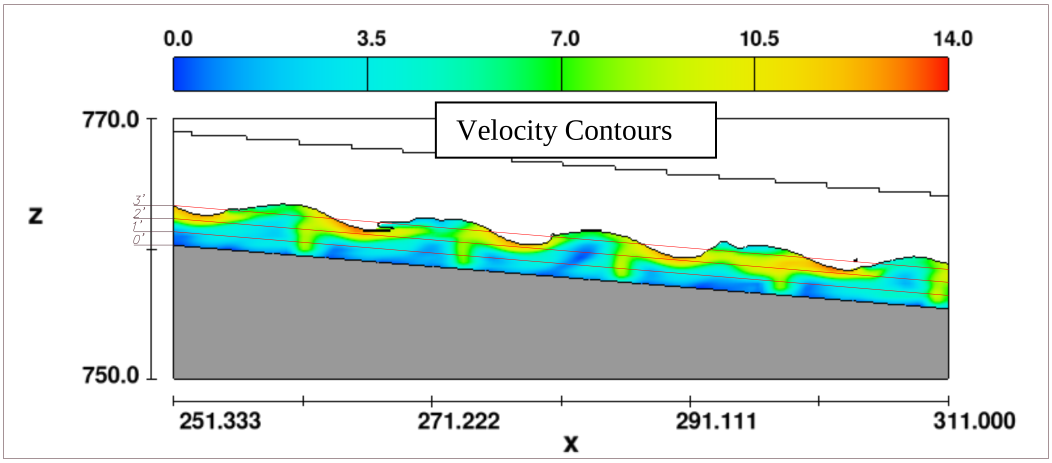


Figure 13 - Baffle C. XZ Section cut through slot 1, see Figure 12.

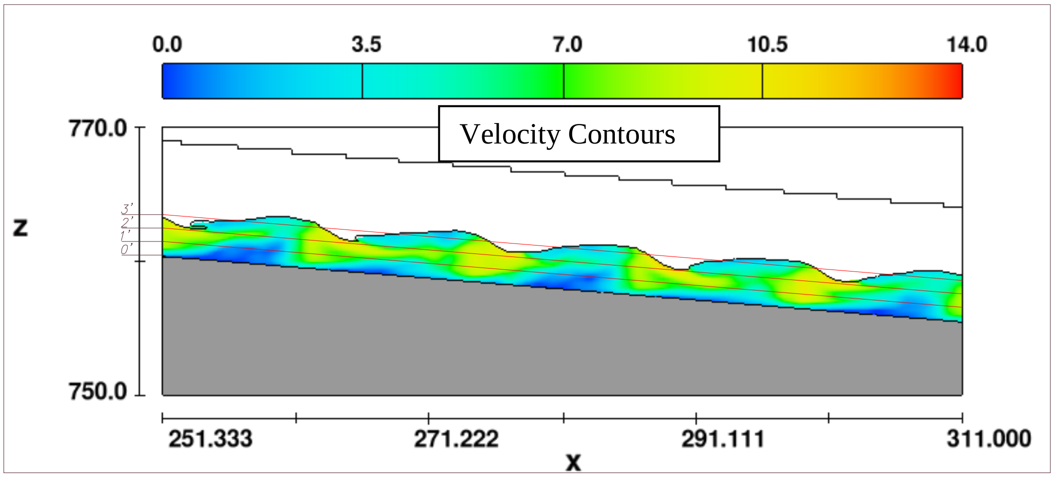


Figure 14 - Baffle C. XZ Section cut through slot 2, see Figure 12.

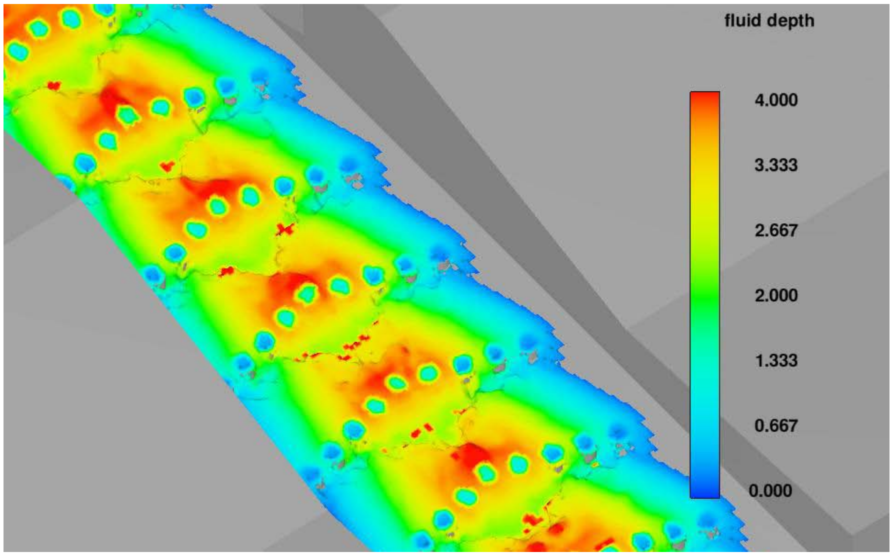


Figure 15 - Fishway flow depth (ft) at 200 ft^3/s flow for Baffle C.

A fourth baffle design labeled Baffle D, was modeled with the slot area on both sides of the center pile reduced from 1 ft to 0.5 ft, (see Figure 4). This simulation was conducted to investigate velocity and depth changes associated with a further reduction of slot flow in the center of the fishway. The slot area was reduced by increasing the diameter of the center pile to 3.0 ft. Surface velocities are shown in Figure 16 and vertical velocity contours along slot lines 1 to 3 (Figure 16) are given in Figures 17 to 19. The change in slot area was small compared to the total flow area; therefore the flow field for baffles "C" and "D" are fairly similar. The most apparent difference in the flow fields is an expansion of low velocity area downstream of each baffle along slot line one, Figure 17.

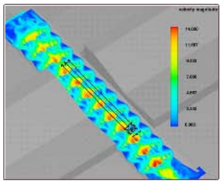


Figure 16- Surface flow velocity in ft/s for Baffle D at 200 ft^3/s fishway flow.

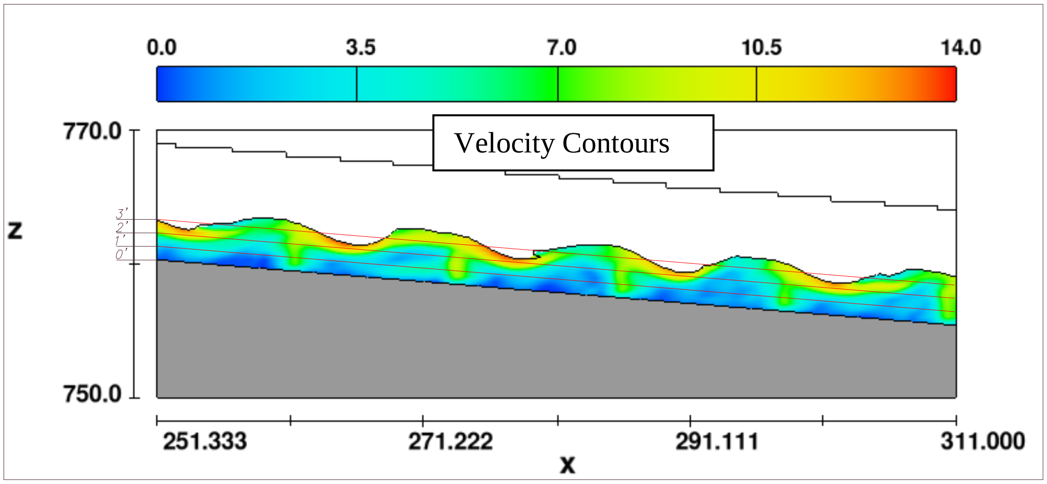


Figure 17- Baffle D, XZ Section cut through slot 1, see Figure 16.

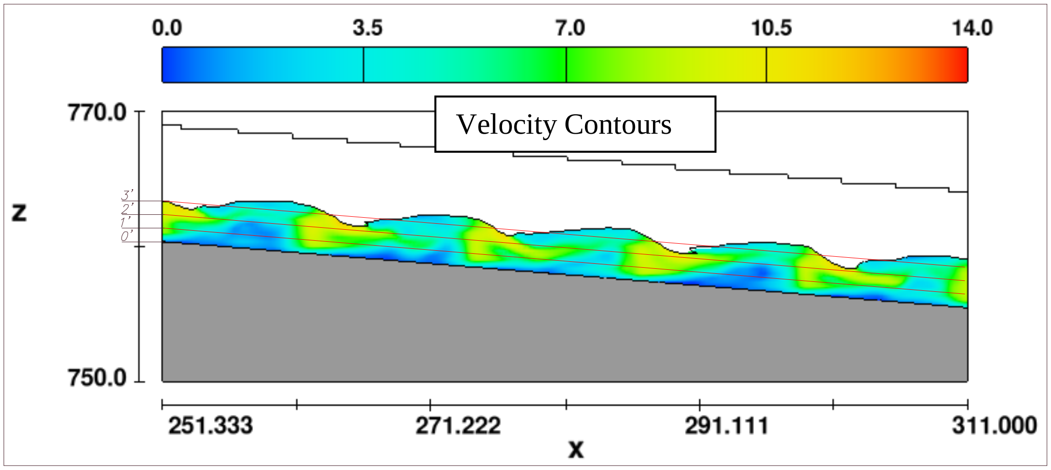


Figure 18 - Baffle D, XZ Section cut through slot 2, see Figure 16.

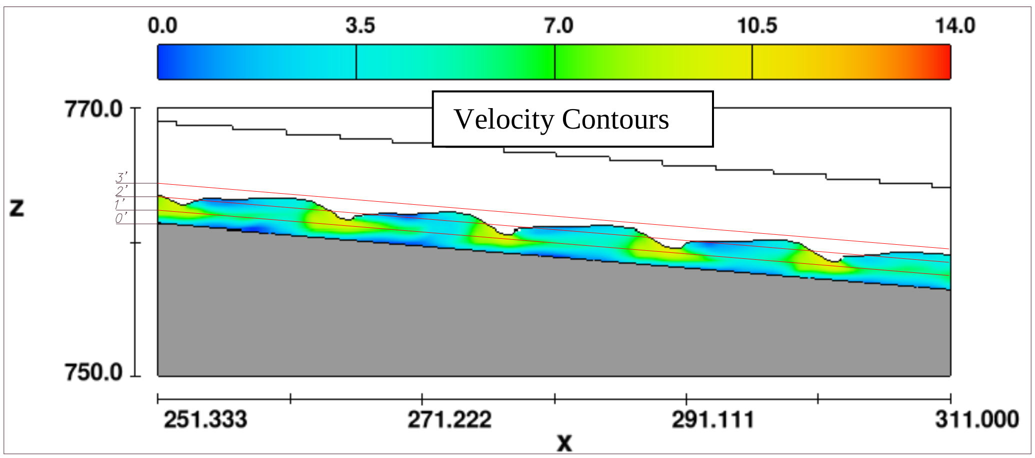


Figure 19 - Baffle D, XZ Section cut through slot 3, see Figure 16.

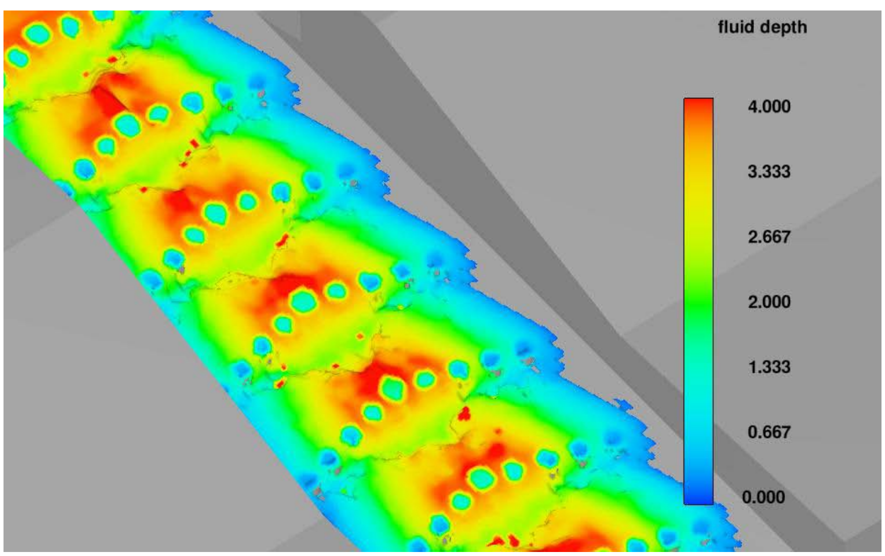


Figure 20- Fishway flow depth (ft) at 200 ft^3/s flow for Baffle D.

Physical Model

A 1:10 Froude-scale physical model of the fishway and a portion of the HFB spillway was constructed at the WRRL (Figure 21). The model included a portion of Robles Diversion Dam, the left most HFB spillway bay, fishway, downstream stilling basin and a section of the rock ramp. A partial width of the HFB spillway was included in the model to simulate tailwater conditions and merging of fishway and spillway flow. The fishway was located similar to the proposed design developed in the HFB spillway study. The entrance is located upstream of the HFB stilling basin endsill on the left side of the leftmost HFB spillway gate. The fishway exit is located on the backside (leftside) of the left spillway gate. Flow enters the fishway through a 20-ft-wide opening with an invert elevation of 766.0. The invert elevation of the fishway exit was fixed at 765.0 to prevent loss of water down the fishway during non-flood conditions. The fishway exit will be gated to allow the diversion pool to rise to elevation 768.0 without release of flow through the fishway. The gate structure was not included in the model as the gate will only be operated in a full open or closed position. The fishway channel was modeled as a riprap-lined trapezoidal channel with an eight-ft-wide bottom and 3:1 side slopes. The downstream rock ramp was also modeled using the similar riprap material as used in the fishway. The HFB spillway gate was modeled as a simple vertical sluice gate.

Physical Model Scaling

Physical model scaling is used to create similitude between model and prototype of major forces controlling the physical processes being studied. Not all forces can be properly scaled simultaneously. Generally, open channel flow problems are modeled based on a Froude scaling relationship. The Froude number relates inertia and gravity forces expressed as, $F_r = v/\sqrt{gd}$ (*v = flow velocity, g = acceleration of gravity and d = flow depth).* Similitude between model and prototype is achieved when the Froude number in the model and prototype are the same. Using Froude scaling the following relationships apply to the 1:10 geometric scale chosen:

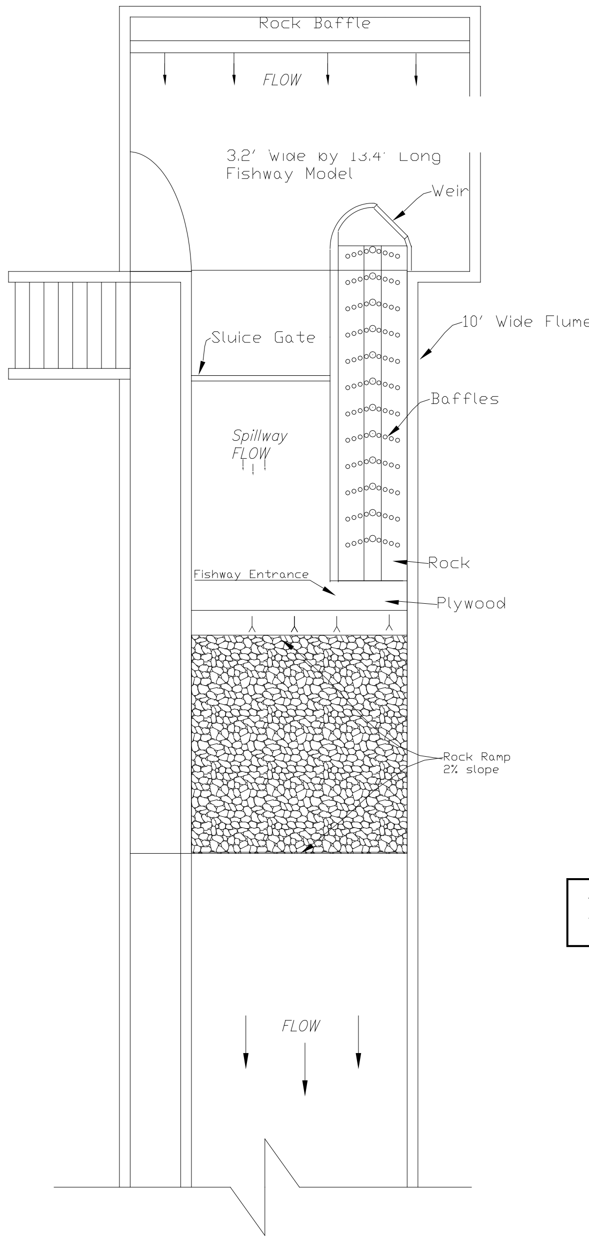
$$L_{p/m} = 10$$

$$V_{p/m} = \sqrt{10} = 3.16$$

$$q_{p/m} = 10^{1.5} = 31.6$$

$$Q_{p/m} = 10^{2.5} = 316.2$$

where: L is length or depth, V is velocity, q is discharge per unit width, Q is discharge and p/m refers to a ratio of prototype to model



Rock Baffle
FLOW
3.2' Wide by 13.4' Long
Fishway Model
Weir
10' Wide Flume
Sluice Gate
Baffles
Spillway
FLOW
Rock
Fishway Entrance
Plywood
Rock Ramp
2% slope
FLOW

Plan View

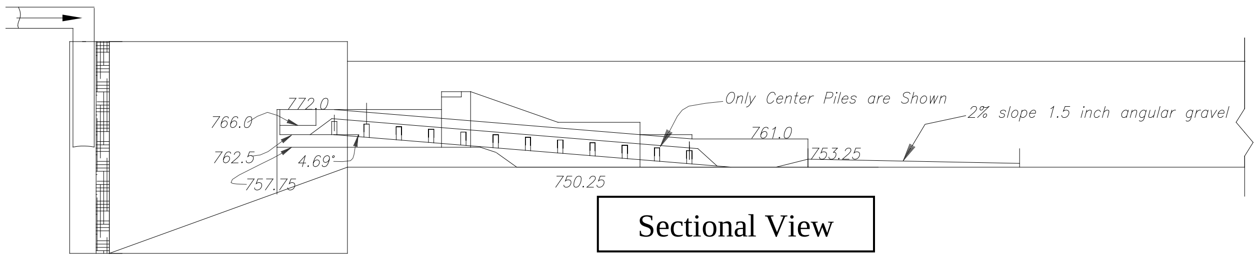


Figure 21 – Plan and sectional view of 1:10 scale physical model.

Fishway Baffle Tests

Baffle configuration “D” was initially installed in the physical model. The model was operated at diversion elevation 768.0 which produced a fishway flow of 160 ft^3/s. Observations of flow conditions in the fishway indicated flow was not sufficient to achieve the desired overtopping of the center piles. The elevation of the exit weir was then lowered to 765.4 which increased fishway flow to about 250 ft^3/s. At the lower exit weir elevation strong skimming flow occurred down the center of the fishway channel. The multiple slot design with overtopping of the three center piles produced a good variety of flow conditions with mid-depth slot velocities measuring about 8 ft/s and lower velocities through the outer slots. An evaluation of debris passage through the fishway was performed by dropping wood material simulating approximately 3 to 5 ft long by 0.25 ft diameter woody debris into the diversion pool. The majority of this material was trapped by the fishway baffles. About 25 percent of the material was carried entirely through the fishway by the flow skimming over the piles in the center of the channel. Although the results of the debris tests were considered as antidotal information, the results clearly indicated narrow slots even with one to two feet of flow overtopping would likely plug during a storm event. A series of quick modifications to the baffle design were then made to investigate possible improvements for debris passage.

The baffle design was changed from ten narrow slots to four wide slots per baffle. This was accomplished in the model by removing the third pile either side of center and then closing several slots to form wider piles. To maintain flow depth, the number of slots was reduced to four. Slots between the center pile and adjacent piles and the slots between the fourth and fifth piles on each side were closed using tape, Figure 22. This resulted in four approximately four-foot-wide (prototype) slots per baffle, one each side of the center pile and one between the outer pile and fishway wall on each side. Limited testing of the modified baffle configuration revealed a significant loss of flow depth and improved debris passage compared to Baffle D. At diversion pool elevation 768.0, the maximum depth in the fishway pools between baffles was about 2.75 ft resulting in little overtopping of the center baffle. Tests of buoyant debris indicated about 60 to 70 percent of the floating material entering the fishway flushed entirely through the fishway. Trapped debris lodged largely against upstream baffle faces near the flow surface and along the channel edges where flow depths were shallow. Some bridging of the 4 ft wide slots by debris was noted as was debris being dislodged by flow after being trapped for a period of time. Major disruption of flow through a slot by debris was not noted in any trials. Observations and water surface measurements revealed the exit weir caused a 15 inch (prototype) drop in the water surface across the weir and a horizontally skewed flow distribution downstream of the weir. The angled exit weir forced significantly more flow to the right side of the fishway resulting in higher flow on the right side than the left for about the upper five baffles. The poor flow distribution was improved by inserting a shallow curved guide wall between the exit weir and the first baffle, Figure 23.

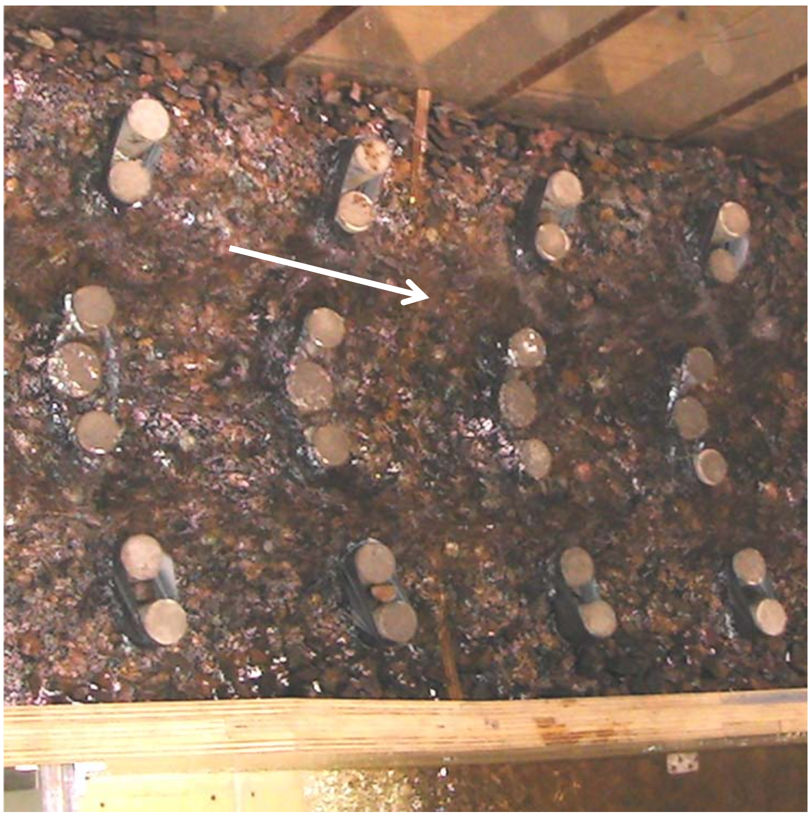


Figure 22 – View looking down the fishway showing flow through the modified baffles. to three piles with four 4-ft-wide flow slots.

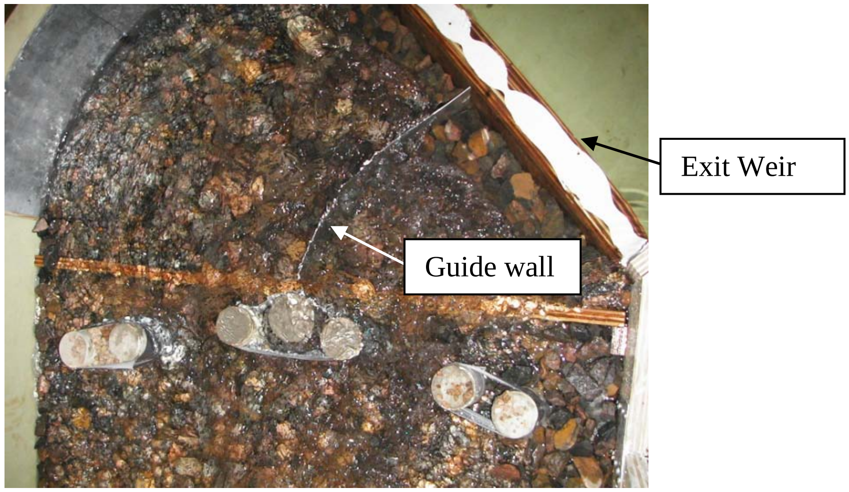


Figure 23 - View of the guidewall installed between the exit weir and upstream baffle.

Modified Fishway Design

Following modification testing the model fishway was rebuilt to implement changes identified during testing. The exit of the fishway was changed to increase fishway flow and reduce the flow skewness created by the exit weir. The crest elevation of the exit weir was lowered to elevation 763.5 and a horizontal weir was installed to elevation 765.2 across the fishway at the start (looking downstream) of the straight chute, Figure 24. Several baffle heights and a center baffle with a shallow "V" notched crest were investigated with the objectives of maximizing debris passage while providing a minimum flow depth of about 3.5 feet in the center of the fishway and an average flow velocity through the slots of about 10 ft/s. The "V" shaped crest was tested to evaluate potential passage and debris flushing benefits of concentrating flow passing over the center baffle. A schematic of the center pile V crest is given in Figure 25. To facilitate ease of investigating baffle height, model baffles were mounted on guide rods set at each baffle location, Figure 26. The height of baffles positioned on each set of rods were then adjusted by adding or removing sections of piles. The cylindrical piles used in the previous tests were replaced by elongated piles with rounded ends. Model piles were milled from high density urethane foam. Figure 27 shows the new baffle arrangement mounted in the model with 3.0 ft high center piles and 3.8 ft high outer piles (referenced to the channel center elevation).

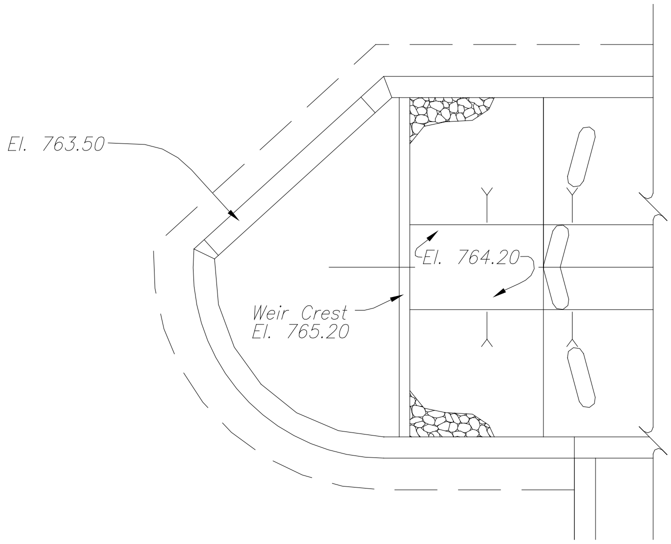


Figure 24 – Plan view showing fishway exit weir and weir added at upstream end of fishway chute.

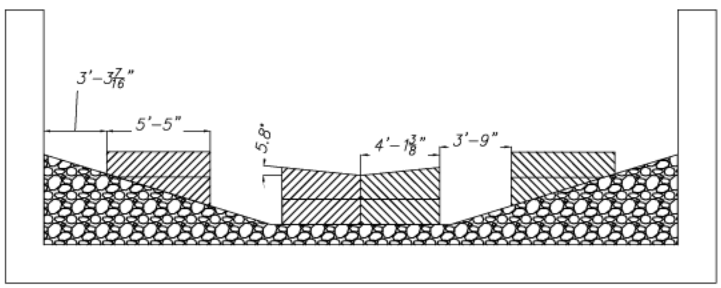


Figure 25 - Sectional view cut along baffle centerline of initial four-slot baffle design.

Figure 26 – Baffle mounting rods used to position fishway baffles in the model.

Figure 27 – Photograph of reconstructed fishway baffles.

Changes to the fishway exit resulted in fishway flow increasing to about 305 ft^3/s at diversion pool elevation 768.0. Flow control shifted from the exit weir to the fishway baffles. With the new fishway weir crest aligned straight with the fishway, the horizontal uniformity of flow approaching the fishway baffles was improved allowing the upstream guidewall to be removed. The model was operated at pool elevation 768.0 while observing fishway flow conditions and debris flushing characteristics. Flow depth through the outer slots was generally less than 1.0 ft which was considered too shallow for effective passage of adult steelhead trout.

The channel shape and baffle design were again modified with the objective of increasing the flow depth through the outer slots. The outer edges of the channel were cut away to create 8.0 ft wide benches on the outer edges of the fishway. The benches set 1.15 ft above the channel thalweg. The outer slot width was reduced to 2.9 ft (34.8 in) by increasing the length of the outer piles. Flow conditions in the revised fishway channel were evaluated for center baffle heights between 2 ft and 4 ft and outer baffle heights between 0 ft and 2 feet. These tests indicated baffles composed of a center pile with the V notched crest set at a notch height 2.4 ft above the channel center and outer piles of height 1.5 ft above the outer bench provided the best flow conditions for achieving fish passage and debris flushing objectives. Plan and centerline profile of the final fishway design are shown on Figure 28. Details of the baffle layout are presented on Figures 29 and 30.

Flow velocity measurements for the final fishway design are presented in Figure 31. Velocity was measured in the model using a 2-D Acoustic Doppler Velocity Meter mounted on an overhead trolley. Shallow flow depths in the physical model limited the locations at which flow velocity could be measured. Velocity measurements were attempted at 0.6 tenths of flow depth. Determining the velocity measurement depth was difficult due to the highly variable water surface, shallow flow depths and large bed roughness. Therefore, the 0.6 tenths depth location reported for velocity measurements is considered to be approximate. Slot velocity was highest downstream of the slot openings in the trough between standing waves created by the baffles. Time-averaged velocity ranged between 6 ft/s and 7 ft/s. Peak instantaneous velocities measured were as high as twice the time-averaged values.

Fishway water surface and depth were measured using a trolley mounted point gage. Water surface profiles were measured along the centerline of the channel and the centerline of the inner and outer slots. The changes to the channel and baffles resulted in flow depth through the outer slots of between 1.5 ft and 2 ft at pool elevation 768.0, (305 ft^3/s fishway flow), Figure 31. Flow depth along a path passing through the center of the inner slots and channel centerline varied between 3 ft and 4.5 ft. Photographs of the model fishway final geometry operating at pool elevation 768.0 are given in Figures 33, 34 and 35.

The fishway will be slowly shutdown following closure of the HFB spillway to encourage fish to move out of the fishway. Fishway flows will decline during the shutdown process by either drawdown of the diversion pool or closure of the isolation gate located atop the exit weir. Model data relating fishway flow depth and diversion pool elevation is given in Figure 36. The data shows all fishway flow will pass through the inner slots (fishway bench areas are dry) when the diversion pool elevation falls below 766.0 ft. The fishway isolation gate was not included in the model and therefore closure simulations based on exit gate operation were not conducted. Development of procedures and duration for shutting down the fishway were not studied in the model and are best accomplished during commissioning of the prototype structure.

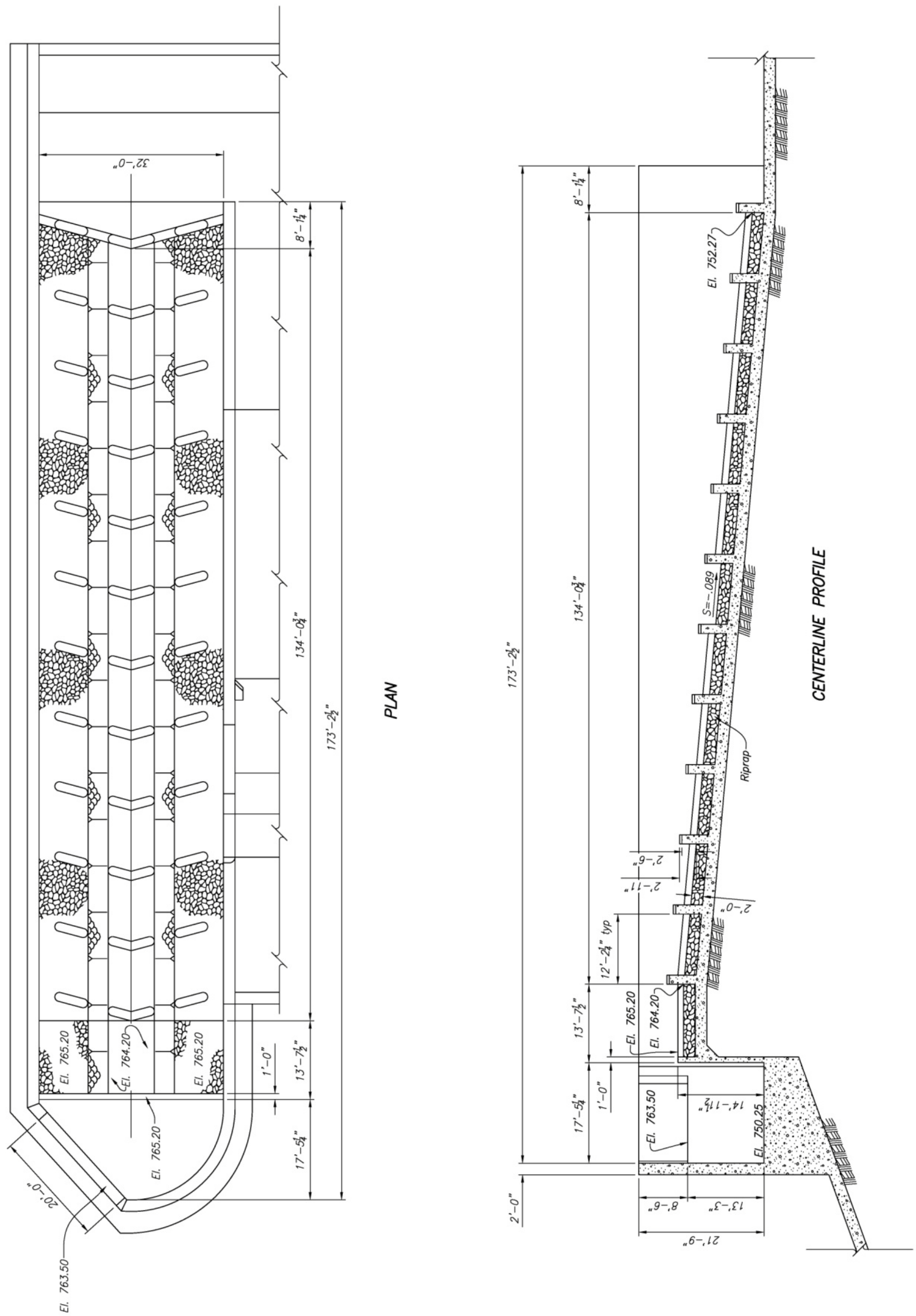


Figure 28 – Plan and centerline profile section of the final fishway design.

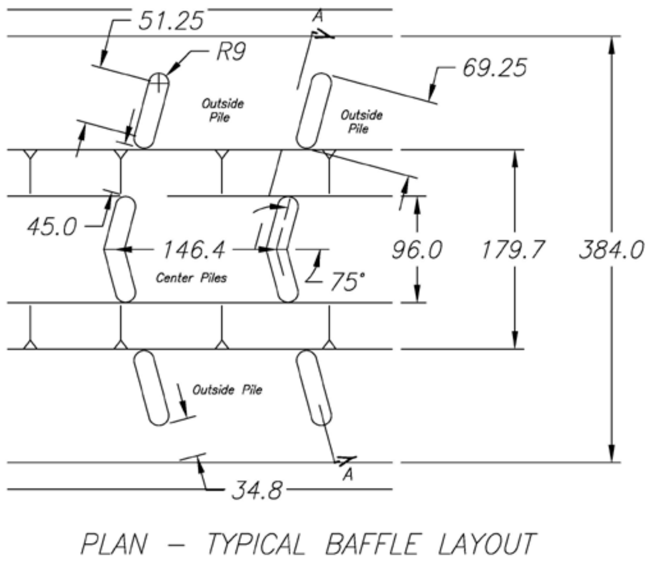


Figure 29– Layout of final fishway baffle design. Dimensions are shown in inches prototype.

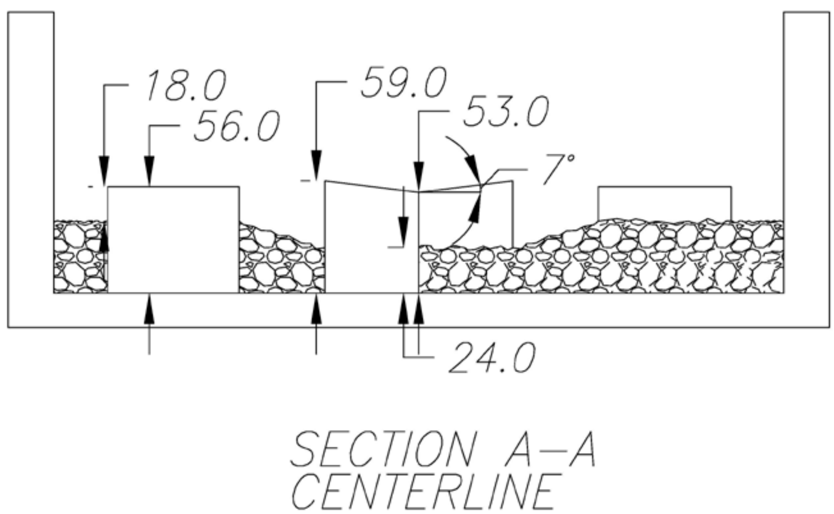


Figure 30 - Sectional view of final fishway baffle design. Refer to Figure 29 for section location. Dimensions are shown in inches prototype.

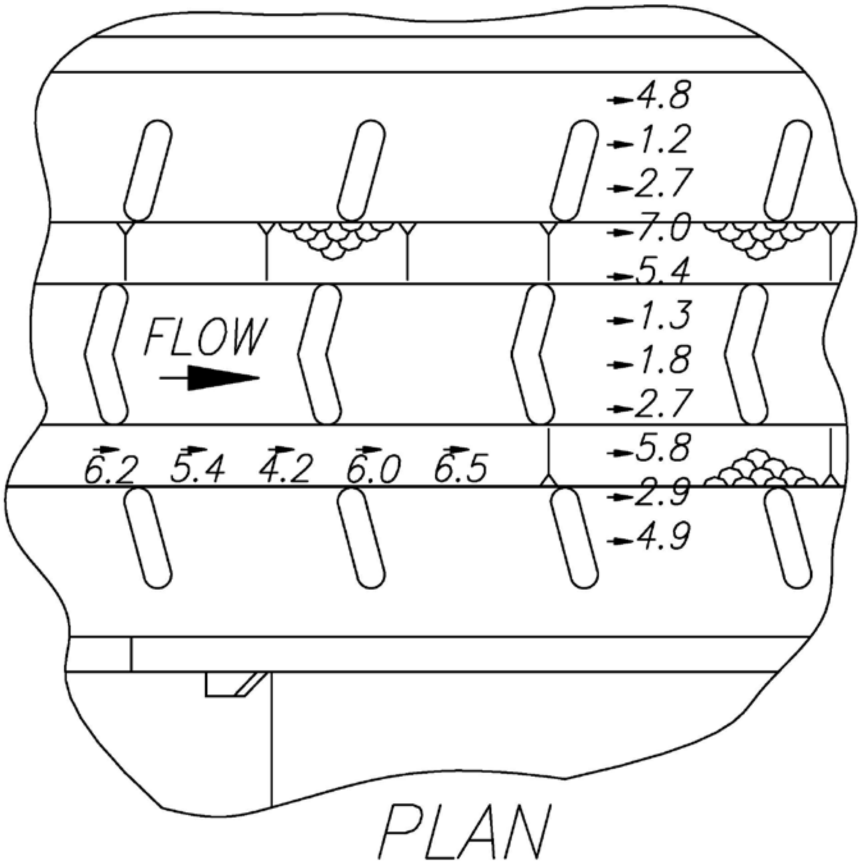


Figure 31 – Plan view of fishway showing location and magnitude of measured flow velocities in ft/s prototype operating at diversion pool elevation 768.0. Velocities were measured at approximately 0.6 tenths depth.

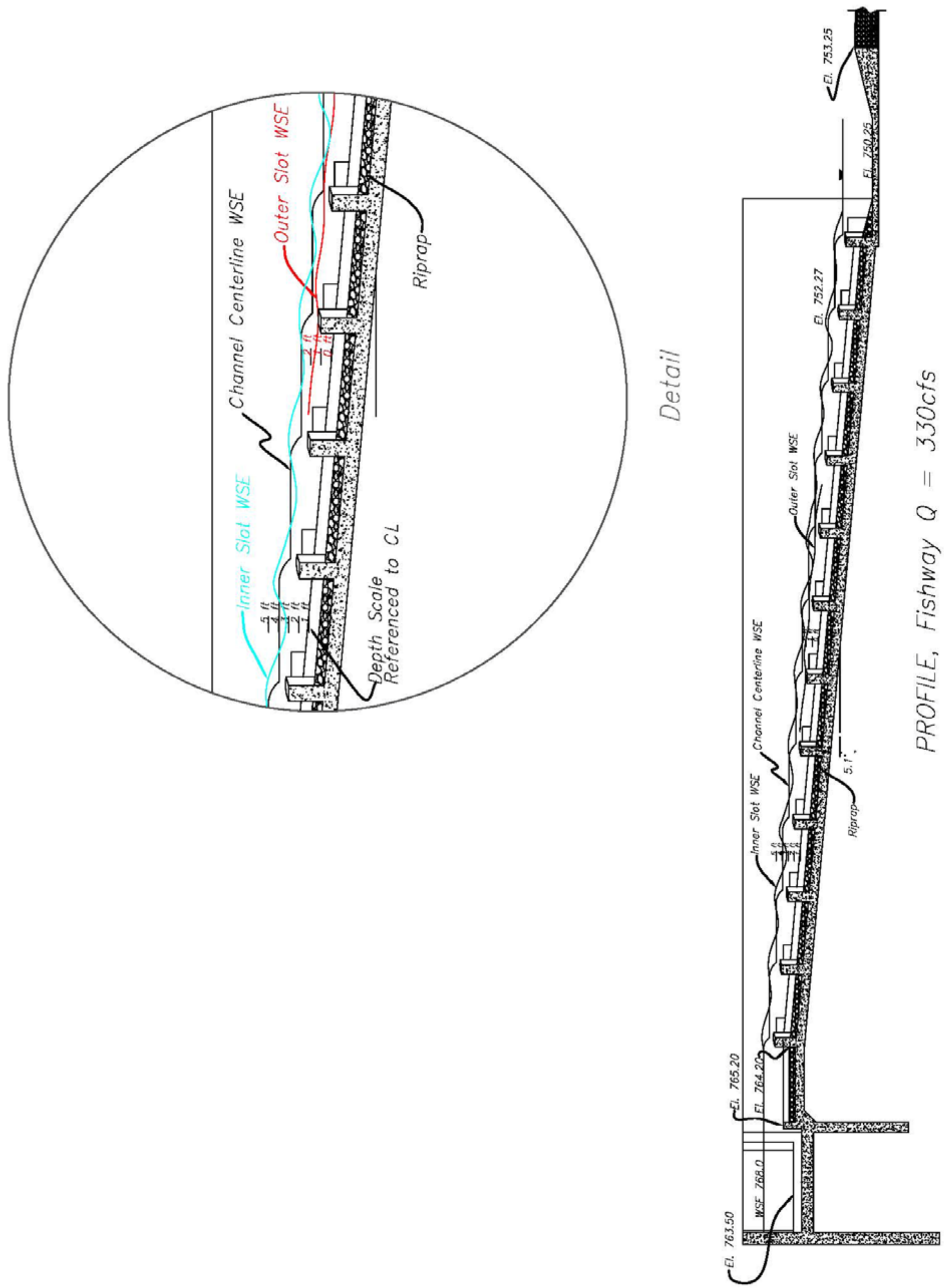


Figure 32 – Section view showing water surface elevations measured in the physical model at the center of the channel, center of the inner baffle slot and center of the outer baffle slot for diversion pool elevation 768.0.

Figure 33– Photograph of the final fishway design showing the fishway exit sill and the fishway weir located at the upstream end of the straight chute. The diversion pool is elevation 768.0.

Figure 34- Photograph of the final fishway design looking upstream toward the fishway exit.

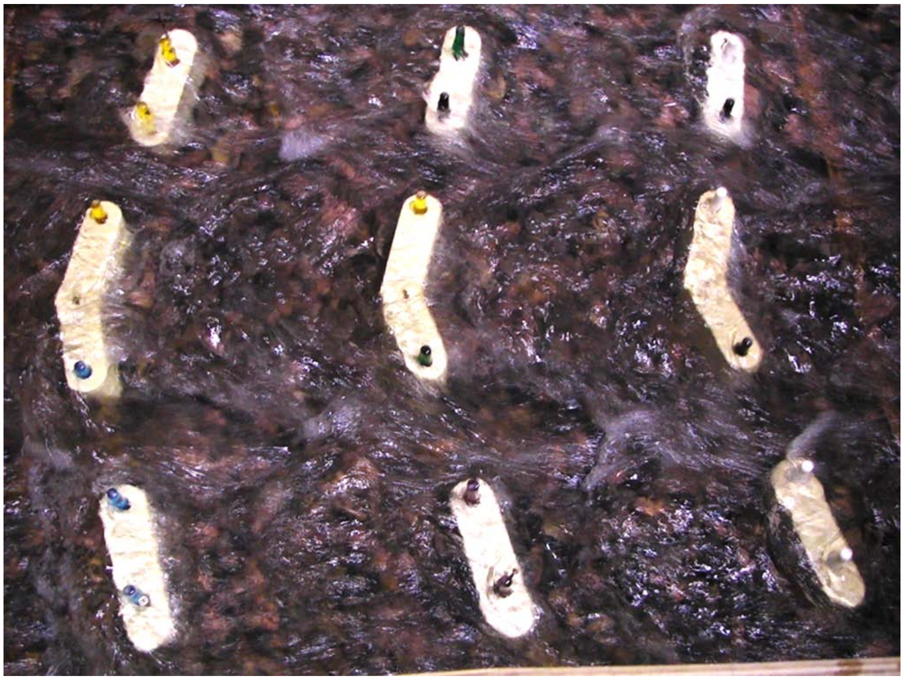


Figure 35– Close-up surface view of flow passing through the recommended fishway baffle arrangement.

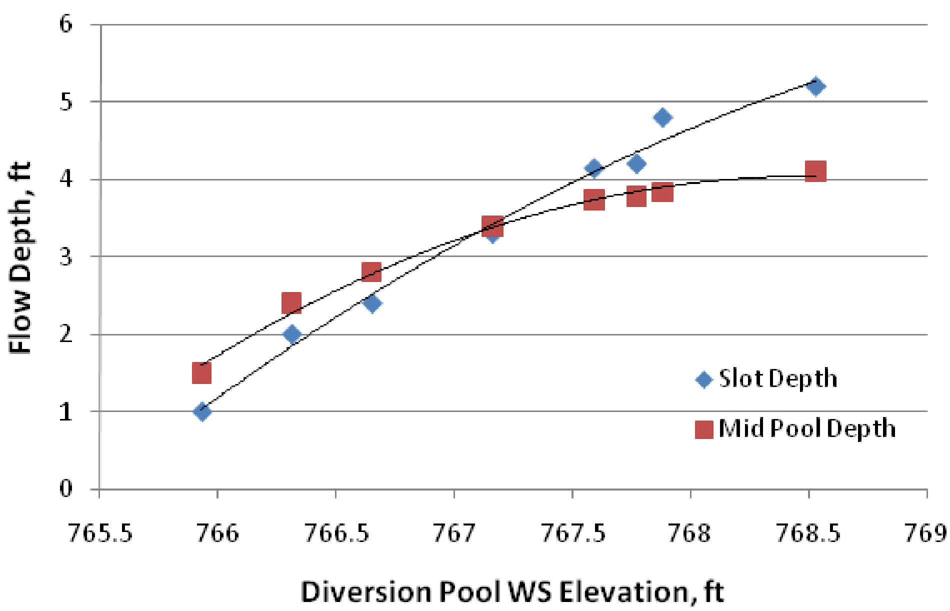


Figure 36 - Fishway flow depth for diversion pool elevations below design.

Numerical Modeling of Fishway Final Geometry

The final fishway design determined from the physical model was numerically modeled using FLOW3D to better document flow velocity and depth conditions beyond what was possible to measure in the physical model. Numerical simulations of the fishway operating at normal diversion pool (El. 768.0) and at high pool (El. 768.5) were conducted. The fishway riprap invert was modeled using a bed roughness of 0.25 ft. The roughness was chosen to represent riprap material ($D_{50} \approx 1.25$ ft) with intestinal voids choked using a graded cobble/gravel/sand material. Choking the riprap matrix in the fishway is recommended to fill large voids. The choke material reduces interstitial flow through the riprap and eliminates large surface depressions that could strand fish during shutdown of the fishway. The X and Y model coordinates referenced in the model output plots is given in Figure 37.

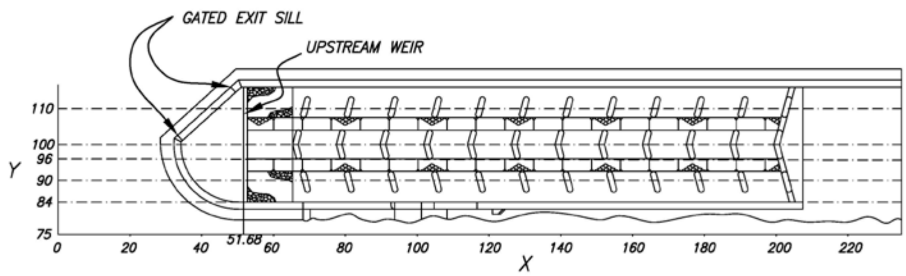


Figure 37 – Plan view showing numerical model X and Y coordinates.

Figures 38 through 42 present flow velocities predicted by Flow3D for the final fishway geometry with the upstream diversion pool water surface set at elevation 768.0. The simulation predicts a flow of 295 ft^3/s through the fishway. Figure 38 presents a plan view of depth average velocity contours within the fishway and downstream basin. Predicted velocities through the baffle slots are higher than the averaged point velocities presented in Figure 31 for the physical model. Peak velocities reported from the physical model more closely compare with numerically predicted velocities. Due to the difficult measurement conditions in the physical model previously discussed, the higher velocities predicted by the numerical simulations are thought to better represent actual flow conditions. Vertical velocity contours through the baffle's inner slot are presented in Figure 39. The sectional view shows flow moves down the fishway inner slots at a velocity of about 10 ft/s. Highest flow velocity (10 ft/s to 13 ft/s) occur in the wave trough downstream of each baffle. Vertical sections showing flow velocities adjacent to the slots are shown in Figures 40 and 41. Flow overtops the fishway baffles by about 1 ft creating three lines of step-pool-cascades. Flow velocity in the pools between baffles is generally less than 4 ft/s with large areas less than 2.5 ft/s. Flow depth between baffles in the center of the fishway (Y=100, Figure 37) is about 3.5 ft. Depth in the outer pools (Y=86, Figure 37) is about 2 ft. A profile of flow velocity through the outer slots is given in Figure 42. Flow velocities are similar to the inner slot with velocities ranging from about 8 to 12 ft/s. Flow depth along the outer slot averages about 1.5 ft. Minimum depth in the wave troughs is about 1.0 ft. Flow depths for the entire fishway are given in Figure 43.

Similar plots of flow velocity and depth for the fishway operating at diversion pool elevation 768.5 are given in Figures 44 through 49 for comparison. The simulation predicts an increase in fishway flow to 385 ft^3/s at pool elevation 768.5. The simulations show fishway flow velocities are similar between normal and high pool operation with fishway flow depth increasing about 0.2-0.3 ft. at high pool.

Conclusions and Recommendations

A minimally baffled fishway was developed for Robles Diversion Dam to provide passage for adult steelhead trout. The fishway is designed to operate as an auxiliary fishway during flood events in excess of about a two year event. An engineered roughened-channel-fishway design is recommended for the project. This type of fishway was selected because large flows needed for fish attraction could be passed directly through the fishway, thus eliminating the need for auxiliary attraction flow facilities. The fishway is designed to convey 300 ft^3/s flow at normal diversion pool (el. 768.0 ft) with flow increasing to about 400 ft^3/s at maximum pool (el.768.5 ft). Key features developed for the design in an effort to provide unimpeded fish passage during debris-laden flood flows are:

- Baffles designed to reduce the probability of debris jams totally blocking passage by incorporating multiple passage routes across each baffle.
- Baffles with wide passage openings (slots) reducing the risk of small woody debris bridging across slots.
- Baffle slots aligned along the fishway creating flow chutes that convey debris straight through the fishway.
- Baffles designed to be overtopped under normal fishway flow facilitating flushing of floating debris.

The recommended fishway design is shown in Figures 28, 29 and 30. The fishway functions as a step-pool type fishway with resting areas located on the periphery of the main flow. Therefore, pools do not serve to dissipate the energy of the main flow. Channel slope, bed roughness and the energy loss due to flow expansion and contraction passing between baffles are the primary controls on passage velocity. Model data predicts average velocity in the passage chutes of about 10 ft/s. Resting pools are spaced at 12.2 ft on center. Fish moving from pool to pool through the baffle slots will encounter 10 ft/s flow for distances less than 10 ft. Passage is also possible for fish passing from pool to pool by jumping or swimming over the baffles. The 8.9 percent slope of the fishway was chosen based on fitting the fishway into the proposed HFB spillway while meeting fish passage flow requirements. The proposed fishway meets passage objectives as set for this study, however during design, opportunities that allow the fishway slope to be reduced should be considered.

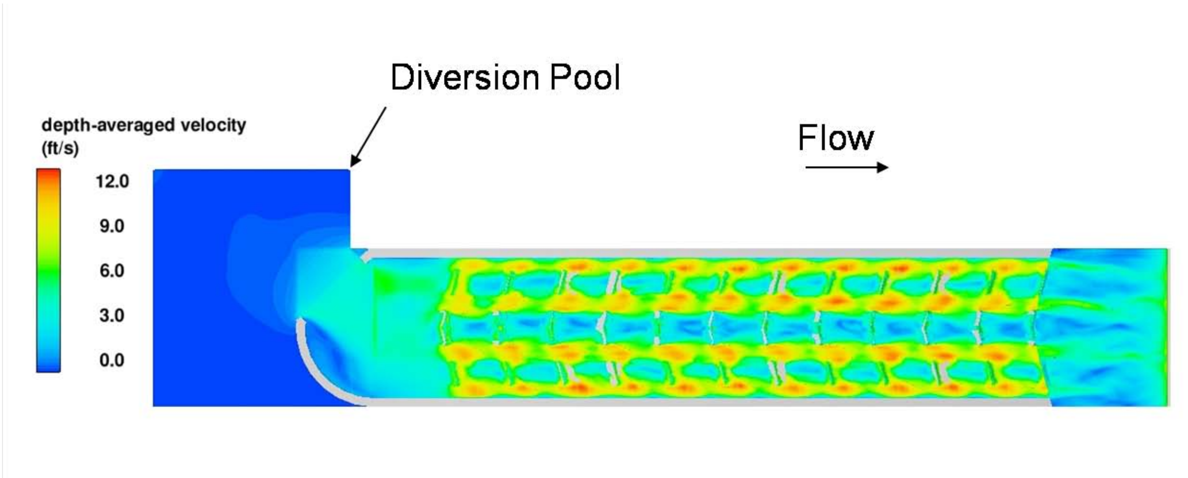


Figure 38 – Plan view showing depth average velocity contours of flow through the final fishway geometry at diversion pool elevation 768.0. Predicted fishway flow is 295 ft^3/s.

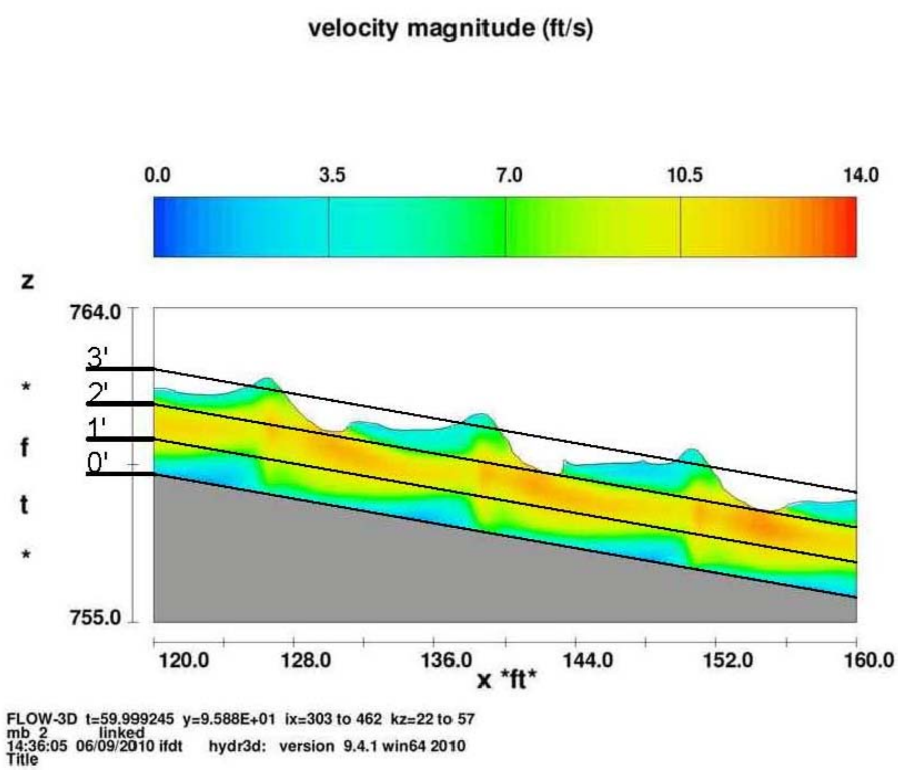


Figure 39 - Elevation sectional view showing flow velocity through the inner slots (see Figure 36 reference location Y=96 ft) at diversion pool elevation 768.5.

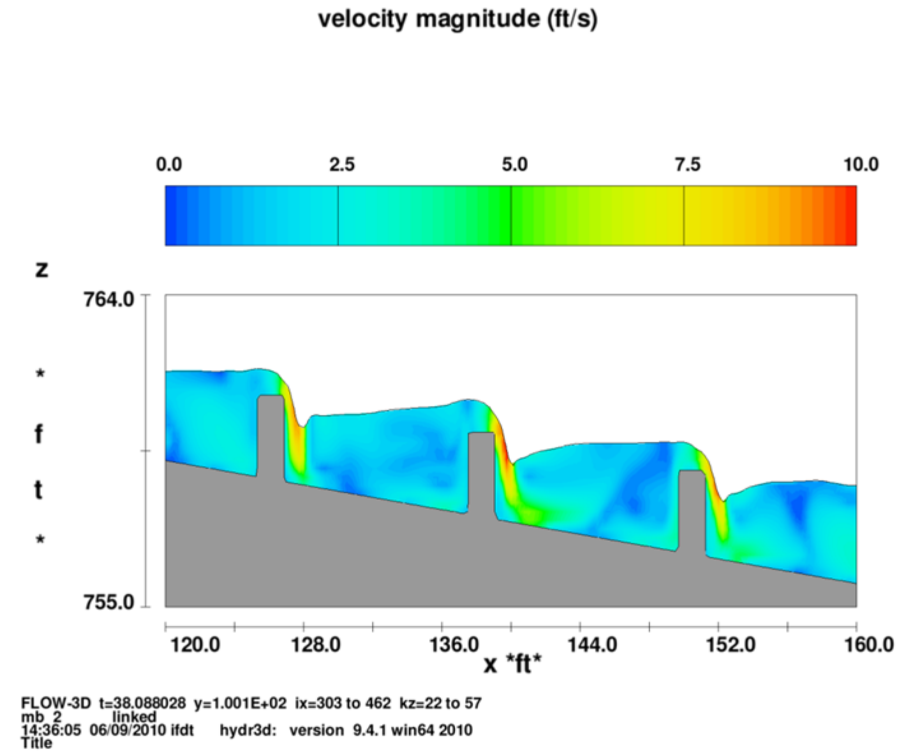


Figure - 40 Elevation sectional view showing flow velocity along the fishway centerline (see Figure 36 reference location Y=100 ft) at diversion pool elevation 768.0.

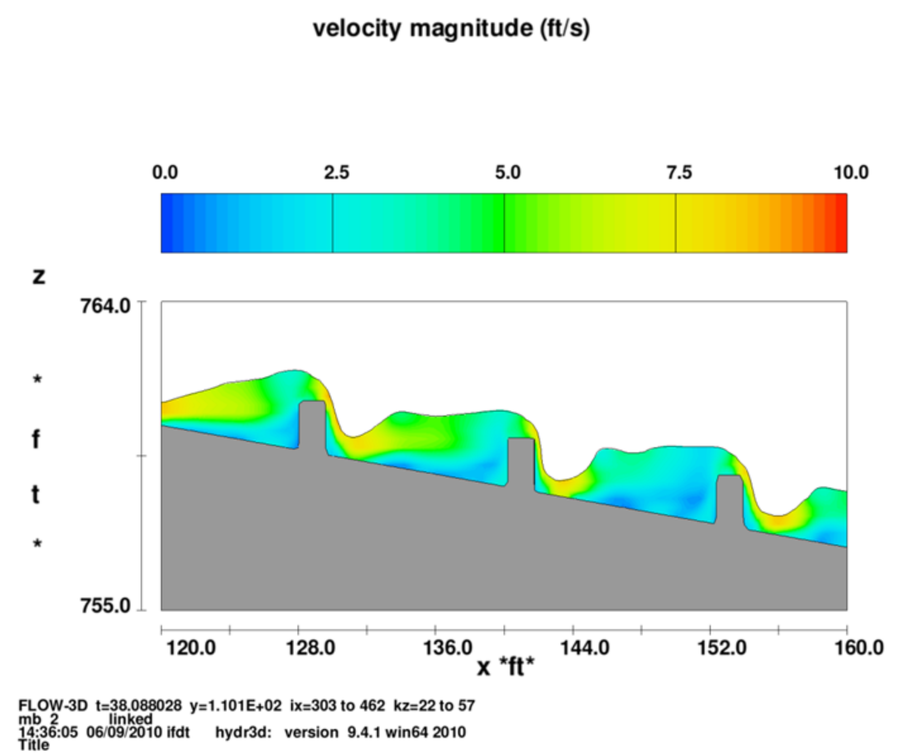


Figure 41 – Elevation sectional view showing flow velocity along the centerline of the outer pile (see Figure 36 reference location Y=110 ft) at diversion pool elevation 768.0.

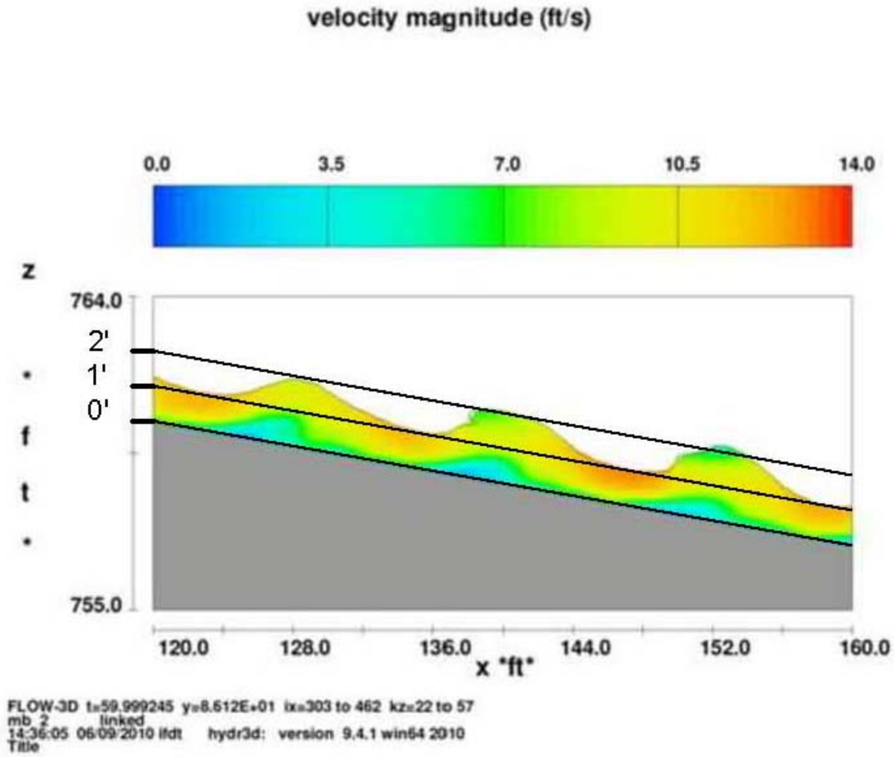


Figure 42 - Elevation sectional view showing flow velocity along the centerline of the outer slot (see Figure 36 reference location Y= 86 ft) at diversion pool elevation 768.0.

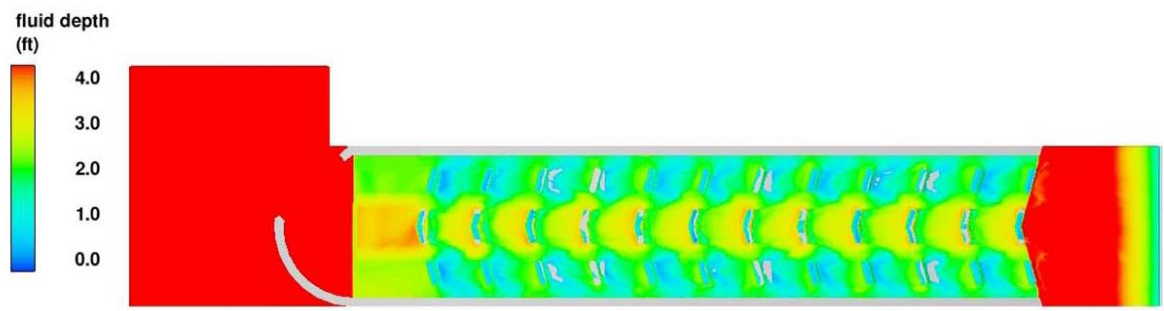


Figure 43 – Plan view showing fishway flow depth predicted by the numerical simulation for reservoir pool elevation 768.0. Fishway flow is 295 ft^3/s.

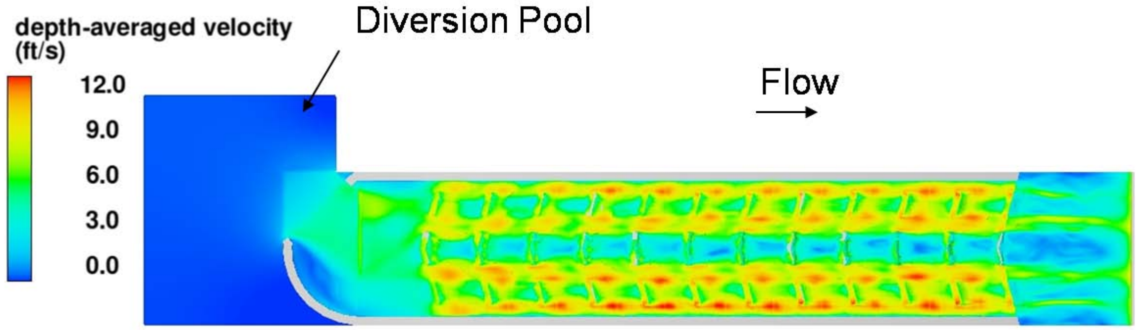


Figure 44– Plan view showing depth average velocity contours of flow through the final fishway geometry at diversion pool elevation 768.5. Predicted fishway flow is 385 ft^3/s.

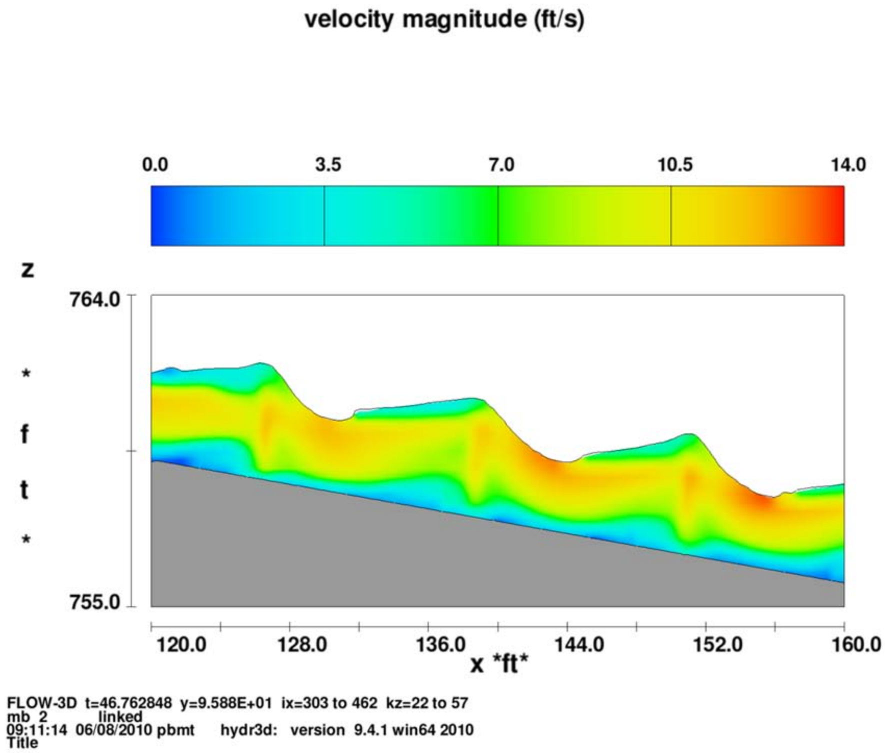


Figure 45 - - Elevation sectional view showing flow velocity through the inner slots (see Figure 36 reference location Y=96 ft) at diversion pool elevation 768.5.

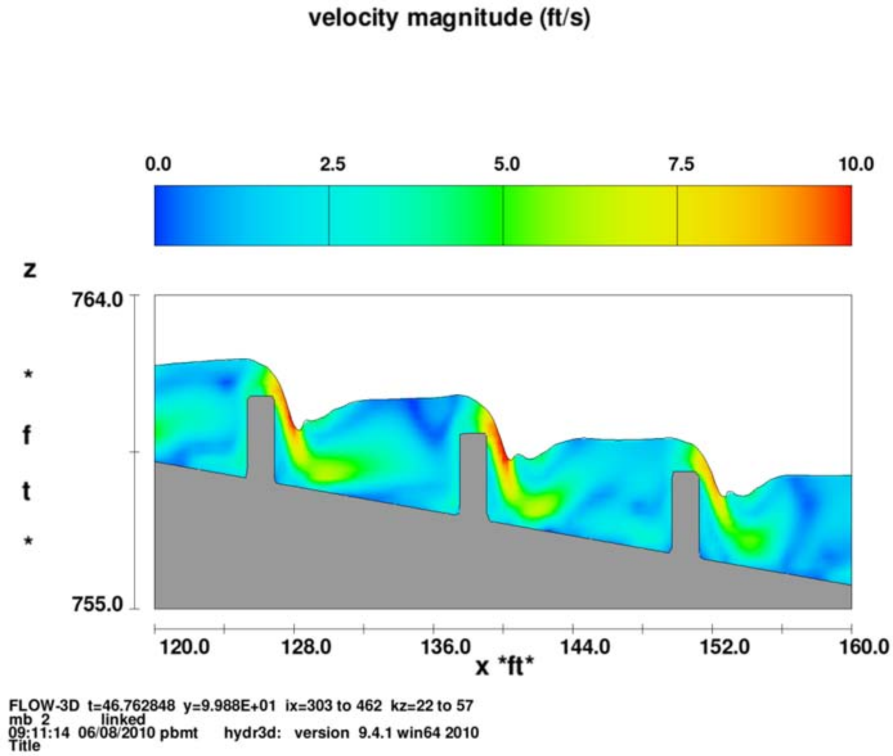


Figure 46 - Elevation sectional view showing flow velocity along the fishway centerline (see Figure 36 reference location Y=100 ft) at diversion pool elevation 768.5.

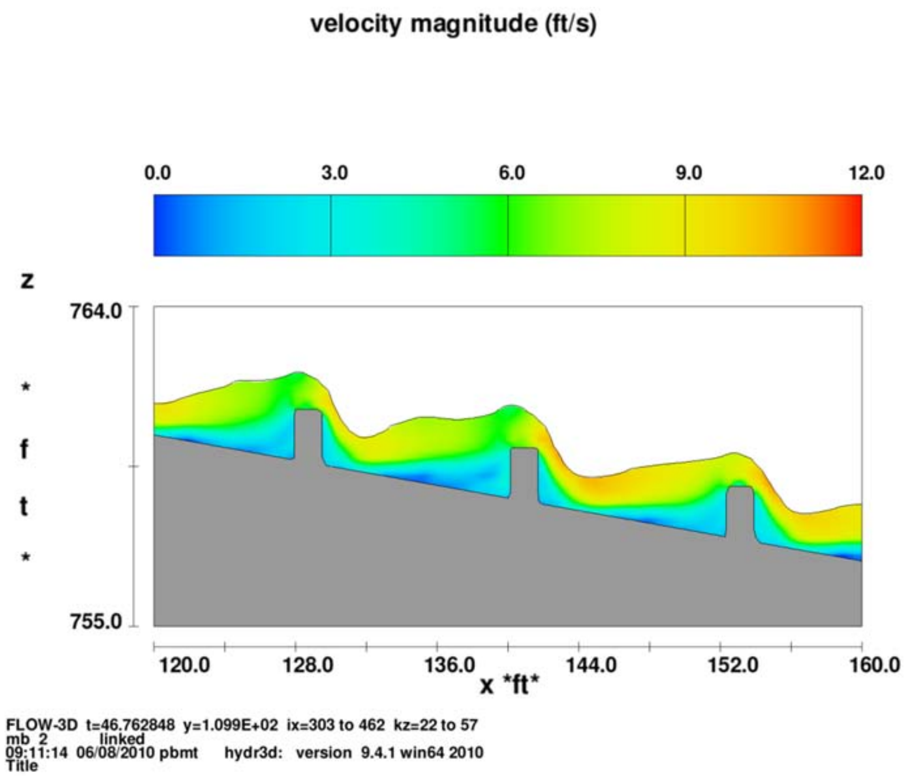


Figure 47– Elevation sectional view showing flow velocity along the centerline of the outer pile (see Figure 36 reference location Y=110 ft) at diversion pool elevation 768.5.

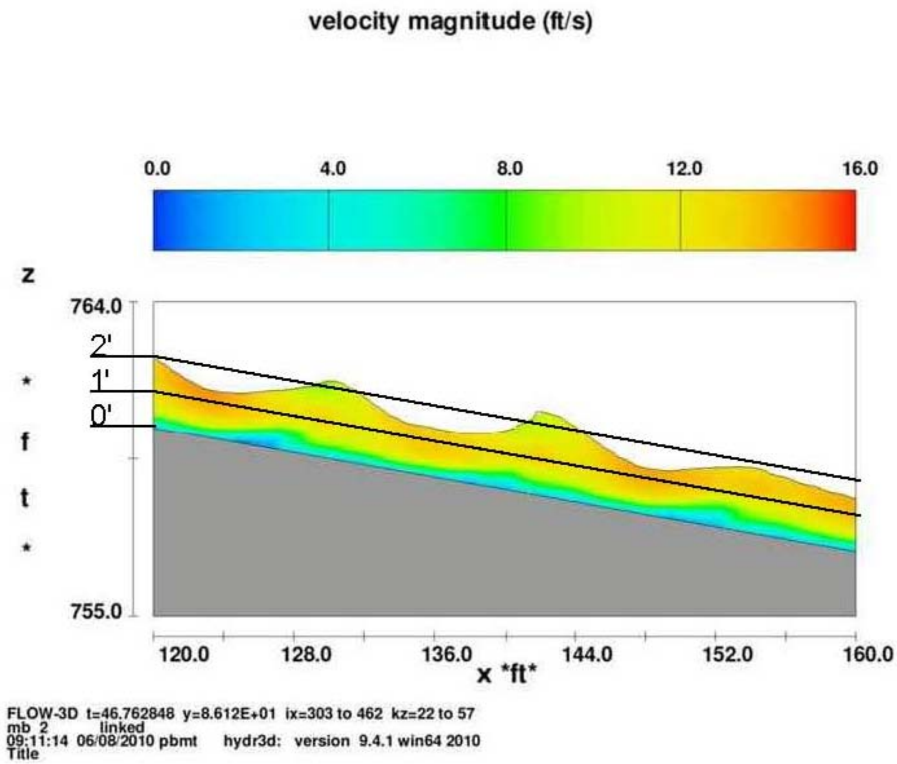


Figure 48 - Elevation sectional view showing flow velocity along the centerline of the outer slot (see Figure 36 reference location Y=86 ft) at diversion pool elevation 768.5.

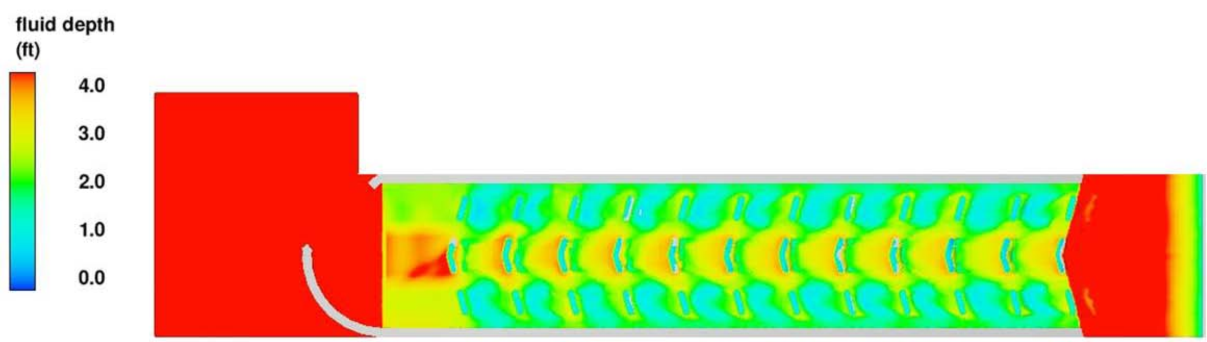


Figure 49– Plan view showing fishway flow depth predicted by the numerical simulation for reservoir pool elevation 768.5. Fishway flow is 385 ft^3/s.

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