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Halfway Wash Fish Barrier Physical Hydraulic Model Study

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14. ABSTRACT

The purpose of the physical hydraulic model study (conducted by Reclamation's Hydraulic Investigations and Laboratory Services group, Denver, Co.) was to develop an effective fish barrier design, to be located on the Virgin River in an area known as Halfway Wash, approximately 16 miles upstream of Lake Mead. The model study was used to test the initial proposed design concept and to optimize performance as a deterrent to upstream passage of non-native species. In addition, because the river bed channel is made up of fine silt and sand, the barrier was also evaluated and optimized for energy dissipation to minimize erosion occurring immediately downstream from the structure.

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Virgin River Fish Barrier Physical Hydraulic Model Study

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Mission Statements

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

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The physical hydraulic model of the fish barrier was constructed by the hydraulics laboratory shop staff, specifically carpenters Jimmy Hastings, Jason Black, and Marty Poos, and machinist Dane Cheek. And thanks to Rudy Campbell for his AutoCAD expertise. Thanks to Spencer Strand and Reclamation's Provo Area office for providing the funding for this project as well as providing the introduction and background for this report. Thanks to Dale Lentz and Kendra Russell for providing HEC-RAS analysis for this study. Also thanks to Brent Mefford for providing technical guidance during the course of this study.

Hydraulic Laboratory Reports

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Disclaimer

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The Virgin River Fishes Recovery Plan (Plan), prepared for the U.S Fish and Wildlife Service by the Virgin River Fishes Recovery Team, outlines the steps necessary to recover the endangered fishes of the Virgin River, and calls for the construction of fish barriers on the river to aid in the eradication of non-native species and the recovery of the endangered species [1]. Fish barriers play a central role in the re-establishment of native fish populations by preventing the current and future upstream migration of invasive, non-native fishes. Once a barrier is constructed, the non-native fish can be eradicated from the river upstream of the barrier and the native populations can be re-introduced to the river. The barrier then prevents future invasion of non-native species, allowing the native fish populations to rebound. The Bureau of Land Management (BLM) assumed the task of overseeing the design and construction of multiple fish barriers. Based on a prior working relationship, BLM and Reclamation entered into an agreement whereby Reclamation would design a fish barrier that would create a vertical discontinuity in the stream surface and increase stream velocities to prevent upstream passage of invasive fish.

The purpose of the physical hydraulic model study (conducted by Reclamation's Hydraulic Investigations and Laboratory Services group, Denver, Co.) was to develop an effective fish barrier design, to be located on the Virgin River in an area known as Halfway Wash, approximately 16 miles upstream of Lake Mead. The model study was used to test the initial proposed design concept and to optimize performance as a deterrent to upstream passage of non-native species. In addition, because the river bed channel is made up of fine silt and sand, the barrier was also evaluated and optimized for energy dissipation to minimize erosion occurring immediately downstream from the structure.

The final fish barrier design developed from this study succeeded in meeting the above criteria. In addition, shallow flow depths over the barrier at flows below 1,000 ft^3/s may serve as an additional deterrent for fish to pass over the barrier. As flows increase above 1,000 ft^3/s, turbulence increases in the area within the roller bucket serving as another deterrent to fish by making it difficult or impossible to stage for a jump in this area.

Patterns of erosion documented for the final barrier design indicate that scour produced downstream from the barrier should not endanger the stability of the structure. However, since a sectional physical model had to be used to represent the barrier, the model performs as if the upstream topography provides uniform approach conditions upstream from the structure, which may not be the case. Therefore this analysis in conjunction with the numerical modeling study conducted by Reclamation's Sedimentation and River Hydraulics group (86-6840) should be used for the final assessment of erosion potential downstream from the structure.

Introduction and Purpose

The lower Virgin River (that portion of the river between the Virgin River Gorge, in the northwest corner of Arizona, and Lake Mead) is home to two native species of fish listed as endangered, the woundfin (*Plagopterus argentissimus*), and the Virgin River chub (*Gila seminuda*). These fish populations are currently under threat due to the upstream invasion of non-native fish from Lake Mead, principally the red shiner (*Notropis lutrensis*) and blue tilapia (*Oreochromis aurea*). The Virgin River Fishes Recovery Plan (Plan), prepared for the U.S Fish and Wildlife Service by the Virgin River Fishes Recovery Team, outlines the steps necessary to recover the endangered fishes of the Virgin River, and calls for the construction of fish barriers on the river to aid in the eradication of non-native species and the recovery of the endangered species [1].

Fish barriers play a central role in the re-establishment of native fish populations by preventing the current and future upstream migration of invasive, non-native fishes. Once a barrier is constructed, the non-native fish can be eradicated from the river upstream from the barrier and the native populations can be re-introduced to the river. The barrier then prevents future invasion of non-native species, allowing the native fish populations to rebound.

The purpose of the physical hydraulic model study (conducted by Reclamation's Hydraulic Investigations and Laboratory Services group, Denver , Co.) was to develop an effective fish barrier design, to be located on the Virgin River in an area known as Halfway Wash, approximately 16 miles upstream from Lake Mead. The model study was used to test the initial proposed design concept and to optimize performance as a deterrent to upstream passage of non-native species. In addition, because the river bed channel is made up of fine silt and sand, the barrier was also evaluated and optimized for energy dissipation to minimize erosion occurring immediately downstream from the structure.

Background

The Bureau of Land Management (BLM) has assumed the task of overseeing the design and construction of multiple fish barriers. Based on an existing working relationship with the Bureau of Reclamation (Reclamation), BLM was aware of Reclamation's design, contracting, construction, and construction management capabilities. Thus, BLM and Reclamation's Provo Area Office (Provo) entered into an agreement whereby Reclamation would provide design, contracting, construction, and construction management services on behalf of BLM in order to construct a fish barrier on the lower Virgin River. This fish barrier will be the lowest barrier on the Virgin River. As such, it will function as the "anchor" barrier. In this particular area, the river valley consists of a wide, relatively flat floor bounded by steep canyon walls. The south abutment rises about 60 feet above the valley floor and the north abutment rises more than 200 feet above the floor. The valley floor itself is about 1,600 feet wide with a maximum elevation change of about 10 feet across its width. Under normal conditions, the main river channel meanders back and forth across the southern third of the valley floor (figure 1). The northern three-quarters of the valley floor lie between four and eight feet higher than the main river channel and are normally dry. Only during very large flood events does the river occupy the entire width of the river valley (figure 2).

The barrier must be designed to prevent upstream passage primarily by creating a vertical discontinuity in the stream surface. BLM provided Reclamation with the basic design requirement that the barrier create a minimum 5-ft-tall vertical jump in the stream surface. At low flows, the barrier will create this discontinuity; however, at moderate to high flows the barrier will be partially submerged and the vertical discontinuity will not fully develop. Therefore, the barrier must be designed to increase stream velocities above the highest dash speed of the invasive fish to prevent upstream movement when the barrier is partially submerged. Based on input from BLM, Reclamation designed the barrier to accelerate stream velocity to 11.5 ft/s whenever the vertical discontinuity criterion was not met.

Figure 1. — Photo montage of the Virgin River valley looking approximately northwest from the south abutment of the barrier. Reclamation photographs by Spencer Strand, 10 December, 2008.

Figure 2. — Photo montage of the Virgin River valley looking approximately northwest from the south abutment of the barrier. Photographs were taken about one day after peak flows of over 20,000 cfs occurred during a flood event. Reclamation photographs by Spencer Strand, 23 December, 2010.

Barrier design

Reclamation's Hydraulic Investigations and Laboratory Service group (86-68460), was tasked with developing the hydraulic design for the proposed fish barrier. The design flow for the structure was given as 45,000 ft^3/s, however, flows in the river channel are more often in the range of 100 ft^3/s to 5,000 ft^3/s. Therefore the barrier had to be designed to perform well throughout this full range of flow conditions. In addition, it is anticipated that flow will concentrate on the left side of the river channel due to the topography of the approach channel and therefore portions of the barrier may experience hydraulic conditions emulating flows of 50,000 ft^3/s or more. An ogee shaped crest is generally considered the most efficient design for passing large flood events and can often be designed based on as little as 75% of the design flood since performance will remain good up to the design flow and cost savings can be significant. For these reasons, an ogee crest shape for the barrier was chosen for the initial crest design, based on a flow of 45,000 ft^3/s. [2].

The next question that had to be addressed was how to maximize energy dissipation while providing an upstream fish deterrent for this range of flow conditions. Although written documentation was not available, past field observations have indicated that a roller bucket design for the barrier energy dissipater, may also serve as a good deterrent to upstream fish passage. The reason this may be true is because the roller bucket produces extreme turbulence in the localized area at the toe of the structure where fish would normally stage to jump over the barrier. The turbulence within the bucket is much more disorganized than would occur in a typical hydraulic jump basin, making it more difficult for them to stage for a jump at that location.

As a result, the initial design for the Virgin River fish barrier consisted of a 5-ft-high ogee-shaped crest, designed for 45,000 ft^3/s, with crest elevation set at 1339 ft, and a roller bucket positioned at the toe of the structure. The invert elevation (El 1334 ft) and radius of the roller bucket were based on a flow of 30,000 ft^3/s since the structure will rarely see flows as high as 45,000 ft^3/s. A roller bucket designed for this discharge should perform reasonably well throughout the full range of flow conditions experienced by the barrier and will save on construction costs. [3]. The initial fish barrier design is shown in figure 3.

Please note that all dimensions within this document are given in terms of the prototype unless otherwise stated. All elevations are relative to the NAD83 datum.

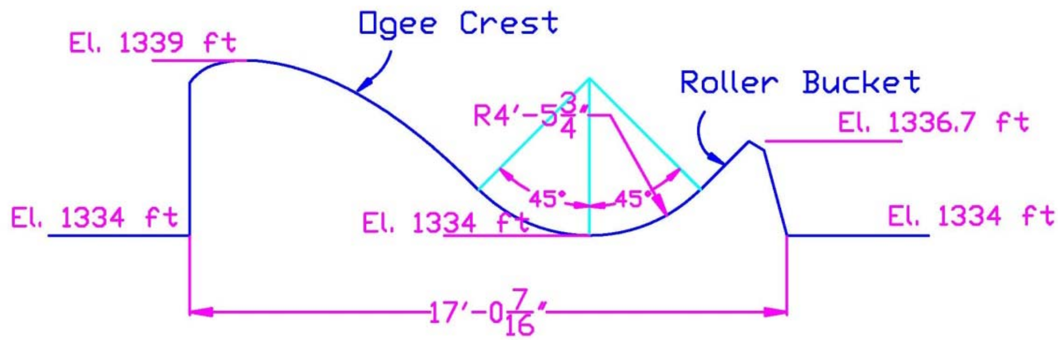

Figure 3. Initial design outline for Virgin River fish barrier #1.

The Model

A physical hydraulic model was constructed at Reclamation's Hydraulic Investigations and Laboratory Services facility in Denver, Colorado.

Because of the extreme width of the river channel, it was not possible to build a full width model of the structure that would adequately simulate the full range of flow conditions experienced by the barrier. Therefore a sectional model was chosen to best represent the structure. A geometric scale of 1:5 was used to construct the model inside an existing flume in the Denver laboratory. The width of the barrier inside the flume represented a 19.75 ft slice across the width of the structure and was constructed from high-density polyurethane.

Since hydraulic performance for open channel flow depends primarily on gravitational and inertial forces, Froude law scaling was used to establish a kinematic relationship between the model and the prototype. Froude law similitude produces the following relationships between model and prototype:

Length ratio $L_r = 1:5$

Velocity ratio $V_r = L_r^{1/2} = 1:2.24$

Discharge ratio $Q_r = L_r^{5/2} = 1:55.9$

Unit Discharge ratio (Q per unit width) = $q_r = L_r^{3/2} = 1:11.18$

Time ratio $T_r = L_r^{1/2} = 1:2.24$

The barrier was installed on top of a platform, constructed inside the flume, so that sand to a 3 ft model-depth could be used for qualitative comparison of scour depths and patterns of erosion for each design tested.

A radius constructed of sheet metal was used to transition from the upstream floor of the flume to the platform, in order to provide a smooth transition for flows approaching the barrier. The platform, constructed of ¾ inch marine plywood, extended a length of 8 model-ft upstream and 10 model-ft downstream from the model barrier to represent a graded elevation of 1334 ft in the field. The layout of the model is shown in figure 4.

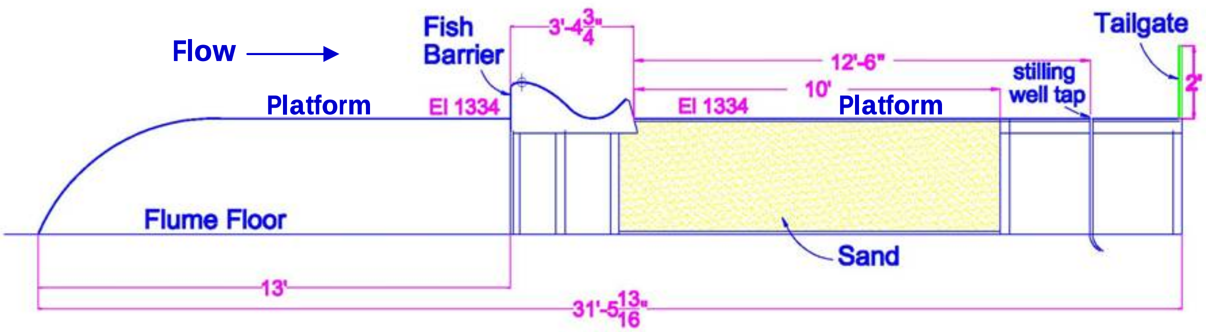

Figure 4 Model Layout shown in model dimensions.

For each flow condition tested, depth and velocity measurements were taken at incremental locations along the length of the structure. Once these measurements were completed for each test condition, the downstream plywood platform was removed and replaced with sand. Because the river channel is made up of fine silts and sand it was not possible to use gradations of materials small enough to accurately represent actual prototype erosion depths. In addition, aggradations of materials swept downstream over the barrier or occurring from upstream flows beyond the sand pit were not simulated in these tests. However, the hydraulic flow patterns and patterns of erosion should be represented reasonably well and qualitative comparisons for each flow condition can be made for different designs to help determine which design provides best performance.

A one dimensional numerical flow model was built using HEC-RAS to generate tailwater elevations for the physical model for each flow condition tested [4]. The numerical model was built using survey cross-section data that was supplied by the Provo area office. The survey extended 1 mile upstream and 2 miles downstream from the proposed fish barrier.

Tailwater elevation in the physical model was controlled with a tailgate installed 15 model-ft downstream from the barrier (figure 4) Tailwater elevation was measured with a point gage in a stilling well tapped into the channel 12.5 model-feet downstream from the roller bucket. The point gage was surveyed in the model relative to the downstream channel elevation. Flow into the flume was routed through a pipe chase surrounding the perimeter of the laboratory and was measured using a calibrated laboratory venturi meter. Reservoir water surface elevation was measured with a staff gage 4 model-feet upstream from the barrier and observed through the flume glass sidewall.

Investigations and Results

For each test condition, flow entering the flume was set and measured using the main laboratory control panels and venture meters. Once flow was set, tailwater elevation in the flume was adjusted with the downstream tailgate until the water surface level reached the level of the corresponding point gage reading for each flow rate tested.

Depth measurements along the barrier were taken through the flume glass sidewall, perpendicular to the urethane surface at half-foot to one foot incremental drops in elevation until tailwater water surface was reached (figure 5). Measured depths were used to calculate average velocities flowing over the barrier at each location. In addition, velocities were also measured with a Swoffer propeller meter about 1.2 model-inches from the crest surface (6 inches prototype) at the model centerline when flow depth was adequate. Velocities measured with the Swoffer meter were not averaged over the full flow depth at any given location, so in most cases the readings are higher than the average velocity calculated using the depth measured near the same location.

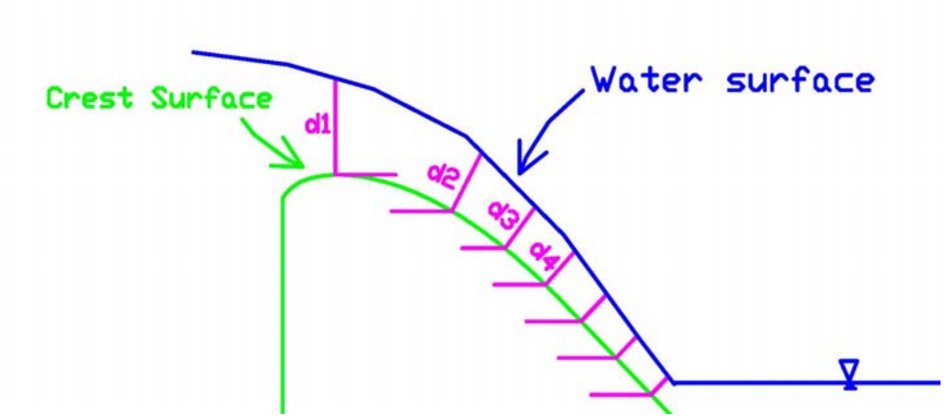

Figure 5. Depth measurements (d#) were taken perpendicular to crest surface at 0.5 to 1.0 ft increments in elevation until flow enters tailwater water surface.

Once flow depths and velocities were measured for each test condition the plywood floor downstream from the barrier was removed and sand was added up to grade elevation 1334 ft. The model was then run continuously for 1 hour segments at each flow rate to qualitatively assess erosion potential for each design. The scour depth and flow pattern resulting from each test was measured, and then documented using photos and video footage.

Virgin River Initial Barrier Design #1

The flow conditions tested for the initial design, with corresponding tailwater elevations, are given in table 1. The stream surface drop was defined as the vertical drop measured from the water surface elevation at the top of the crest to the tailwater elevation at the bucket invert. This distance as well as the maximum velocity measured just before flow enters the tailrace is given for each flow rate tested in table 2. The flow depth, calculated velocity, and measured velocity (when applicable) for each flow condition and corresponding location are given in tables 3-8.

Table 1 Flow Conditions Tested

Prototype Discharge (ft^3/s)	Prototype Tailwater Elevation (ft)
200	1335.11
1,000	1335.80
10,000	1338.68
20,000	1339.93
30,000	1341.08
45,000	1342.48

Table 2. Stream surface drop and maximum velocities for barrier design #1.

Prototype Discharge (ft^3/s)	Stream Surface Drop (ft)	Maximum Calculated Prototype Velocity (ft/s)	Maximum Measured Prototype Velocity (ft/s)
200	2.33	4.0	N/A
1,000	2.45	10.1	N/A
10,000	1.92	12.1	13
20,000	1.5	12.5	13.6
30,000	1.17	12.8	14.3
45,000	0.52	13.2	14.2

Table 3. Initial barrier design - velocities for 200 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Soffer Propeller meter (ft/s)
1339.0	0.175	1.43	N/A
1338.5	0.060	3.33	N/A
1337.0	0.050	4	N/A

Table 4. Initial barrier design - velocities for 1,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Swoffer Propeller meter (ft/s)
1339.0	0.325	3.1	N/A
1338.5	0.145	6.7	N/A
1337.0	0.10	10.0	N/A

Table 5. Initial barrier design - velocities for 10,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Swoffer Propeller meter (ft/s)
1339.0	1.6	6.25	7.9
1338.5	1.025	9.75	10.73
1338.25	0.825	12.12	13

Table 6 Initial barrier design - velocities for 20,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Swoffer Propeller meter (ft/s)
1339.0	2.43	8.25	10
1338.5	1.7	11.76	12.5
1338.25	1.6	12.5	13.6

Table 7 Initial barrier design - velocities for 30,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Swoffer Propeller meter (ft/s)
1339.0	3.25	9.23	12.1
1338.5	2.43	12.37	12.3
1338.25	2.35	12.77	14.3

Table 8 Initial barrier design - velocities for 45,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Swoffer Propeller meter (ft/s)
1339.0	4.2	10.7	13.2
1338.5	3.50	12.8	14.1
1338.25	3.4	13.2	14.2

Tables 3 through 8 show that at flows of 10,000 ft^3/s and above, although stream surface drop criteria is not met, flow velocities entering at tailwater elevation, meet the required criteria to deter upstream fish passage for both methods of measuring velocity. In the range of 200 ft^3/s to 1,000 ft^3/s neither velocity criteria or minimum stream surface drop is achieved. The elevation of the roller bucket for this design was based on producing maximum energy dissipation for the range of flows being considered. Since the downstream edge of the roller bucket was set at elevation 1336.7 ft, for any flow where natural tailwater forms below this elevation, a pool was formed at the toe of the structure that was higher than the value given in table 1. This was true for flows of 200 ft^3/s and 1,000 ft^3/s, where the tailwater at the toe of the structure pools to elevations 1336.85 ft and 1336.87 ft respectively. Therefore the stream surface drop, and thus velocities entering the water surface at the toe of the structure, were reduced at the lower flows due to the higher water surface at the toe of the structure.

Because the bucket was designed based on criteria specified in Reclamation's Engineering Monograph No. 25 and Design of Small Dams, to minimize the potential for erosion, erosion data was documented for this design and was used as the baseline for comparing erosion potential for subsequent designs [2] [3]. This data will be presented in the Erosion Testing section of this report.

Virgin River Barrier Design #2

Since fish barrier criteria was not met with the initial design for all flow conditions, the model was modified to better utilize the drop from the crest to tailwater, to help increase velocities entering into the tailrace for the lower flow rates.

For the modified design, the design and elevation of the ogee crest was left intact and the roller bucket was lowered along the bucket's 45 degree tangent line, until the highest edge of the bucket was flush with elevation 1334 ft. This also caused the roller bucket to move about 2 ft (prototype) downstream from its original location for a new prototype structure length of 19 ft-1/4 inch, and new bucket invert elevation of 1331.32 ft (figure 6)

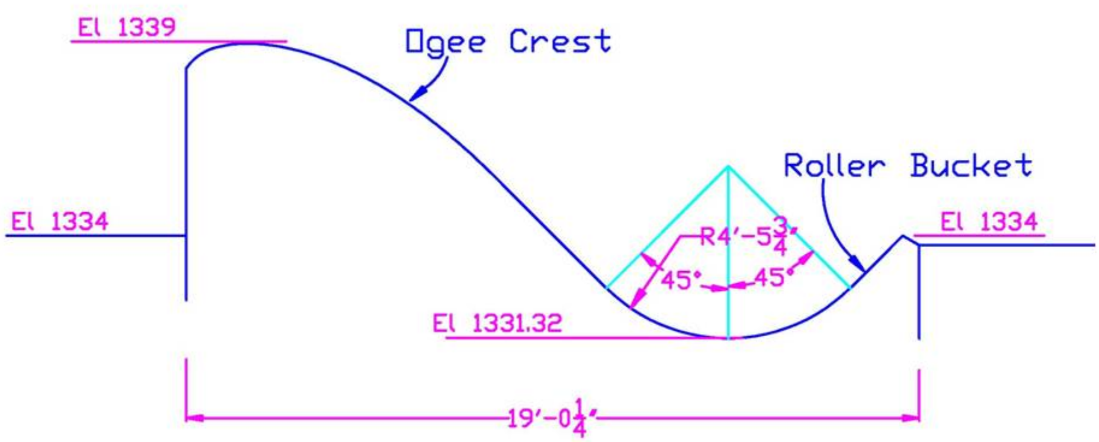

Figure 6. Outline of Barrier #2 design.

Identical flow conditions to those tested previously, were evaluated for this design. The stream surface drop (vertical distance from the water surface measured above the top of the crest to the tailwater water surface) as well as the maximum velocity entering the tailrace for each test condition are given in table 9. The table shows that although the stream surface drop has increased, it is still below the 5 ft drop criteria for all flow conditions tested. Tables 10-15 give the flow depth, calculated velocity, and measured velocity (when applicable) for each flow condition tested, at the corresponding elevations where depth measurements were taken.

Table 9. Stream surface drop for barrier design #2

Prototype Discharge (ft^3/s)	Stream Surface Drop (ft)	Maximum Calculated Prototype Velocity (ft/s)	Maximum Measured Prototype Velocity (ft/s)
200	4.03	10.3	N/A
1,000	3.53	12.8	N/A
10,000	1.83	12.9	14
20,000	1.42	13.0	15.1
30,000	0.92	13.0	14.7
45,000	0.72	13.8	15.5

Table 10 Barrier design #2 - velocities for 200 ft^3/s

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Swoffer Propeller meter (ft/s)
1339.0	0.14	1.43	N/A
1338.5	0.07	3.1	N/A
1337.5	0.04	5.12	N/A
1336.5	0.03	7.7	N/A
1335.5	0.02	10.26	N/A

Table 11. Barrier design #2 - velocities for 1,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Swoffer Propeller meter (ft/s)
1339.0	0.33	3.1	N/A
1338.5	0.14	7.14	N/A
1337.5	0.10	10.0	N/A
1336.5	0.09	11.11	N/A
1335.5	0.08	12.82	N/A

Table 12. Barrier design #2 - velocities for 10,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Swoffer Propeller meter (ft/s)
1339.0	1.51	6.62	8.6
1338.75	1.05	9.52	10.8
1338.5	0.83	12.0	12.7
1338.25	0.78	12.9	14.0

Table 13 Barrier design #2 - velocities for 20,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Swoffer Propeller meter (ft/s)
1339.0	2.35	8.51	10.9
1338.75	1.85	10.81	12.9
1338.5	1.6	12.5	14.3
1338.25	1.53	13.0	15.1

Table 14 Barrier design #2 - velocities for 30,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Swoffer Propeller meter (ft/s)
1339.0	3.0	10.0	12.3
1338.75	2.6	11.35	13.0
1338.5	2.4	12.5	14.5
1338.25	2.3	13.0	14.7

Table 15 Barrier design #2 - velocities for 45,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Swoffer Propeller meter (ft/s)
1339.0	4.0	11.25	13.8
1338.75	3.54	12.7	14.9
1338.5	3.38	13.32	15.3
1338.25	3.25	13.8	15.5

The tables show that this time velocity criteria is met for flow rates greater than or equal to 1,000 ft^3/s. At 200 ft^3/s, velocities are closer to meeting criteria with this design, but they are still below 11.5 ft/s.

Although each measurement was taken using a conservative approach (and later verified using a point gage), because of the scale that was used to encompass the large range of the flow conditions to be tested in the model, a small error in depth measurement at the lowest flow in the model (due to small waves on the water surface) can produce a large error in the value of the prototype velocity. For example, at a flow of 200 ft^3/s, an error in depth measurement of 1/16th inch in the model can produce an error in prototype velocity of up to 50 percent too high. That same 1/16 inch error in depth measurement would produce errors of less than 8 percent and 4 percent for flow rates of 5,000 ft^3/s and 10,000 ft^3/s respectively. In addition, velocities could not be measured with the Swoffer meter at flow rates below 5,000 ft^3/s, because flow depth was not adequate.

Because of the reasons stated above and since the velocity criterion was still not met at the lowest flow tested, it was determined that the best way to ensure that either the velocity or water-surface drop criteria was achieved for all flows was to raise the crest elevation high enough to meet surface drop criteria for flows of 1,000 ft^3/s or less.

Virgin River Barrier Design #3

The next step that was discussed with the Provo office, was to raise the elevation of the crest by 2 ft in order to ensure stream surface drop criteria was met when velocity criteria was not. However, before the proposed crest could be raised to a higher elevation, an analysis had to be conducted to determine to what extent the crest raise would affect properties located upstream from the location of the barrier.

River Reach Affected by 2 ft Crest Raise

An analysis was conducted to determine the length of river, upstream from the Virgin River fish barrier, that would be affected by the barrier. The one dimensional HEC-RAS model that was used previously to generate tailwater data for the physical model was modified to determine the upstream area that would be affected by the barrier. The survey extended 1 mile upstream and 2 miles downstream from the proposed fish barrier. The river in this reach has an average slope of 0.002. For this analysis, the farthest upstream cross section was used as a template and extrapolated upstream 3 additional miles (4 miles from the barrier). This simplified approach assumes a constant slope of 0.002 and a generic cross section during the interpolated 3 mile reach.

The model was then run using the new extended river geometry. Using this analysis, the proposed fish barrier (crest elevation 1341 ft) would produce a backwater effect in the river that extends approximately 1.5 miles upstream from the barrier (figure 7). The water surface of the river, beyond 1.5 miles upstream from the barrier, will see little or no effect from the proposed fish barrier. This simplified analysis should not be used to determine the exact water surface elevation in the interpolated portion of the model, but only as an indicator as to the reach that is affected by the proposed fish barrier. This calculation also does not account for long term, large scale sediment transport effects of the proposed barrier. However, it is unlikely that changes in sediment transport would be seen this far upstream. The sediment transport modeling being conducted by Reclamation's Sedimentation and River Hydraulics group (86-6840) as a separate study, should provide insight to whether the proposed barrier affects transport rates further upstream.

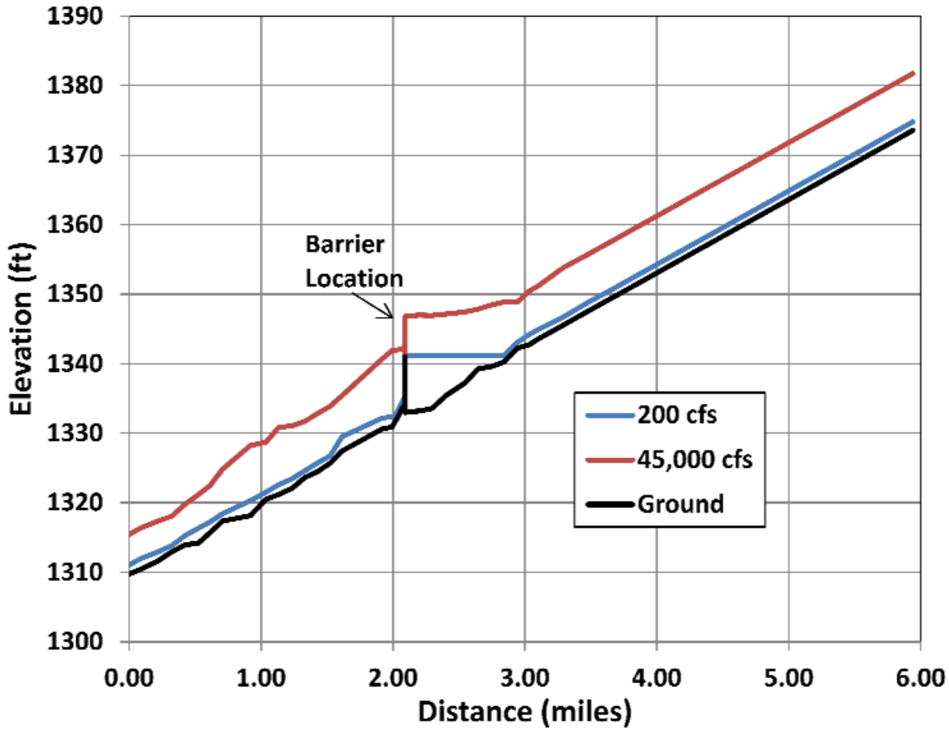

Figure 7. Approximate water surface elevation in vicinity of the proposed fish barrier.

The Provo office agreed that these were all reasonable assumptions and approved the 2 foot crest raise for testing in the model.

Barrier Design #3

As a result of this analysis it was agreed that the fish barrier model would be modified by raising the crest elevation by 2 feet. This was done by moving the crest upward along the same 45 degree tangent line that was used to lower the roller bucket previously. This moved the crest 2 ft (prototype) upstream from its previous location for a new total length of 21 ft- 7/16 inch. However the original crest shape and the roller bucket from Design#2 were both left intact (figure 8)

The same flow conditions tested previously were used to evaluate the new design, however, two new flow conditions (600 ft^3/s and 5,000 ft^3/s) were added to get a closer look at the hydraulic conditions for flows below 10,000 ft^3/s. HEC-RAS was again used to establish tailwater elevations for the new configuration, including the two additional test flows. Table 16 shows the flow rates with corresponding tailwater elevations that were tested for barrier design #3.

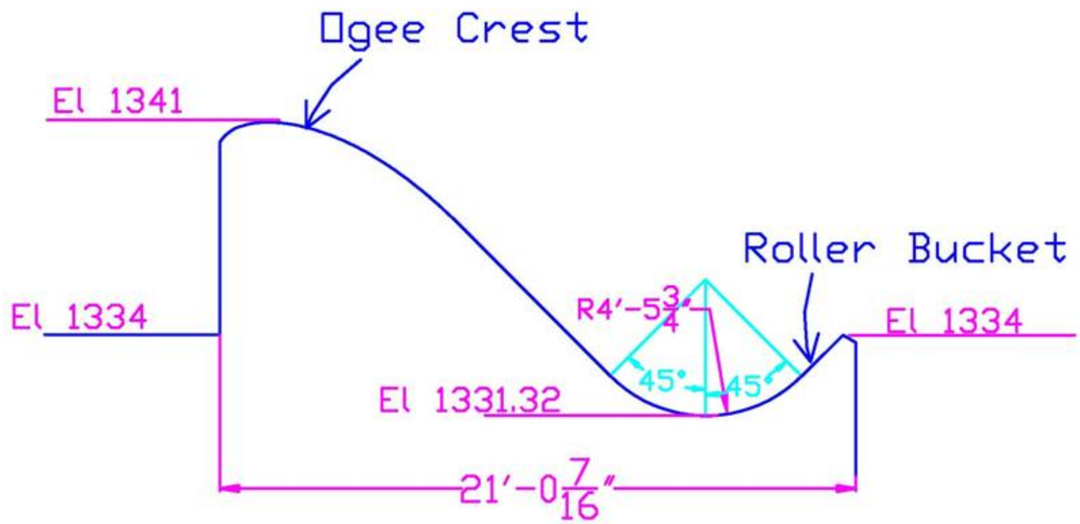

Figure 8. Outline for the final design for the Virgin River fish barrier (barrier design #3)

Table 16 Flow conditions tested for barrier design #3.

Prototype Discharge (ft^3/s)	Prototype Tailwater Elevation (ft)
200	1335.11
600	1335.53
1,000	1335.80
5,000	1337.48
10,000	1338.68
20,000	1339.93
30,000	1341.08
45,000	1342.48

Table 17. Barrier Design #3 -- Stream surface drop and maximum velocity.

Prototype Discharge (ft^3/s)	Stream Surface Drop (ft)	Maximum Calculated Prototype Velocity (ft/s)	Maximum Measured Prototype Velocity (ft/s)
200	6.1	8.0	N/A
600	5.7	11.5	N/A
1,000	5.5	15.4	N/A
5,000	4.5	16.0	N/A
10,000	3.9	15.4	16.3
20,000	3.5	16.0	19.4
30,000	2.9	16.7	19.2
45,000	1.7	18.2	19.2

Table 18 Barrier design #3 - velocities for 200 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Soffer Propeller meter (ft/s)
1341.0	0.182	1.1	N/A
1340.5	0.104	1.9	N/A
1340.0	0.072	2.8	N/A
1339.5	0.078	2.6	N/A
1339.0	0.052	3.8	N/A
1338.5	0.052	3.8	N/A
1338.0	0.052	3.8	N/A
1337.5	0.046	4.4	N/A
1337.0	0.039	5.1	N/A
1336.5	0.039	5.1	N/A
1336.0	0.033	6.1	N/A
1335.5	0.026	7.7	N/A
1337.25	0.024	8.3	N/A

Table 19. Barrier design #3 - velocities for 600 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Soffer Propeller meter (ft/s)
1341.0	0.260	2.3	N/A
1340.5	0.156	3.8	N/A
1340.0	0.111	5.4	N/A
1339.5	0.104	5.8	N/A
1339.0	0.098	6.1	N/A
1338.5	0.091	6.6	N/A
1338.0	0.091	6.6	N/A
1337.5	0.075	8.0	N/A
1337.0	0.075	8.0	N/A
1336.5	0.065	9.23	N/A
1336.0	0.059	10.2	N/A
1335.5	0.052	11.5	N/A

Table 20 Barrier design #3 - velocities for 1,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Soffer Propeller meter (ft/s)
1341.0	0.339	2.9	N/A
1340.5	0.195	5.1	N/A
1340.0	0.156	6.4	N/A
1339.5	0.133	7.5	N/A
1339.0	0.117	8.5	N/A
1338.5	0.104	9.6	N/A
1338.0	0.091	11.0	N/A
1337.5	0.078	12.8	N/A
1337.0	0.075	13.3	N/A
1336.5	0.065	15.4	N/A

Table 21 Barrier design #3 - velocities for 5,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Soffer Propeller meter (ft/s)
1341.0	1.016	4.9	6.0
1340.5	0.560	8.9	9.5
1340.0	0.495	10.1	11.9
1339.5	0.443	11.3	13.1
1339.0	0.417	12.0	N/A
1338.5	0.391	12.8	N/A
1338.0	0.35	14.3	N/A
1337.5	0.335	14.9	N/A
1337.0	0.313	16.0	N/A

Table 22 Barrier design #3 - velocities for 10,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Soffer Propeller meter (ft/s)
1341.0	1.602	6.2	7.8
1340.5	1.042	9.6	11.2
1340.0	0.86	11.6	13.1
1339.5	0.807	12.4	13.9
1339.0	0.755	13.2	15.3
1338.5	0.677	14.8	16.3
1338.0	0.651	15.4	16.3
1337.5	0.651	15.4	N/A

Table 23 Barrier design #3 - velocities for 20,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Soffer Propeller meter (ft/s)
1341.0	2.474	8.1	10.3
1340.5	1.771	11.3	13.3
1340.0	1.51	13.2	14.1
1339.5	1.458	13.7	17.1
1339.0	1.354	14.8	18.1
1338.5	1.289	15.5	19.2
1338.0	1.250	16.0	19.4

Table 24 Barrier design #3 - velocities for 30,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Soffer Propeller meter (ft/s)
1341.0	2.995	10.0	13.2
1340.5	2.318	13.0	15.1
1340.0	2.083	14.4	17.5
1339.5	1.953	15.4	18.2
1339.0	1.797	16.7	19.2

Table 25 Barrier design #3 - velocities for 45,000 ft^3/s.

Elevation on Barrier Surface (ft)	Prototype Depth Perpendicular to Barrier Surface (ft)	Calculated Prototype Velocity (ft/s)	Measured Velocities with Soffer Propeller meter (ft/s)
1341.0	3.167	14.2	14.3
1340.5	2.969	15.2	17.3
1340.0	2.747	16.4	19.2
1339.5	2.539	17.7	19.3
1339.0	2.474	18.2	19.2

The stream surface drop as well as the maximum velocity entering the tailrace for each test condition is given in table 17. The flow depth, calculated velocity, and measured velocities (when applicable) for each flow condition and corresponding locations are given in tables 18-25.

The tables show that for this design, stream surface drop is met for flows less than or equal to 1,000 ft^3/s and velocity criteria is met for the remaining flow conditions tested. Thus, this design was accepted as the final fish barrier design.

Erosion Testing

Quantitative erosion testing could not be conducted using the physical model because the small-sized materials in the river bed could not be scaled down to accurately represent gradations sampled in the field. However, although actual scour depths could not be simulated, the patterns of erosion that would occur could be reasonably represented in the model using fine sand. Therefore erosion tests with sand were conducted to get qualitative data on resulting erosion patterns.

To conduct these tests, the platform immediately downstream from the barrier was removed and sand to a model depth of about 3 ft was installed to a prototype surface bed elevation of 1334 ft. Erosion testing was conducted for barrier #1 for each flow rate tested since the roller bucket for this design was optimized to minimize erosion. These data were used for comparison with the final barrier design #3 to get a qualitative assessment for the effectiveness of the final design in minimizing erosion. For the two barrier designs, the minimum flow rate (200 ft^3/s) and corresponding tailwater elevation was set and then left to run continuously for one hour (2.24 hours prototype). Just before the end of the time segment, maximum scour depth was measured and documented along with the distance from the barrier (referenced to downstream edge of the roller bucket) where it occurred. Then flow was slowly increased to the next flow rate and tailwater adjusted accordingly. This process was repeated for each flow rate. Table 26 shows the scour depths and corresponding distance, for each flow rate tested for barriers #1 and #3.

The data shows that for flows up to 1,000 ft^3/s erosion occurs close to the downstream edge of the bucket for both designs. Erosion occurs next to the structure with low discharges because velocities are low, therefore flow at the end of the bucket tends to drop vertically downward over the downstream edge and erosion does not go very deep for either design (figure 9). For barrier design #1

Figure 9. Erosion pattern after running model at 600 ft^3/s (barrier #3).

the edge of the bucket is further above the river bed channel, so the greater drop causes a scour depth that is slightly deeper. However, barrier design #3 has a greater total drop, from the crest elevation to the bucket invert. Therefore velocities at the end of the bucket are higher and erosion is pushed a little further downstream and isn't quite as deep.

Figure 10 Final Design (barrier #3) – Model operating at 5,000 ft^3/s.

Figure 11 Final Design (barrier #3) – Model operating at 5,000 ft^3/s.

Figure 12 Final Design (barrier #3) – Model operating at 10,000 ft^3/s.

Figure 13 Final Design (barrier #3) – Model operating at 10,000 ft^3/s.

Figure 14 Final Design (barrier #3) – Model operating at 20,000 ft^3/s.

Figure 15 Final Design (barrier #3) – Model operating at 20,000 ft^3/s.

Figure 16 Final Design (barrier #3) – Model operating at 30,000 ft^3/s.

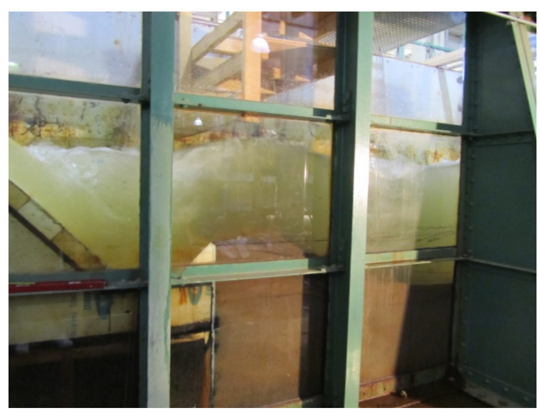

Figure 17 Final Design (barrier #3) – Model operating at 30,000 ft^3/s.

Figure 18 Final Design (barrier #3) – Model operating at 45,000 ft^3/s.

Figure 19 Final Design (barrier #3) – Model operating at 45,000 ft^3/s.

Figure 20 Final fish barrier design #3 - Erosion pattern after operating model at 10,000 ft^3/s.

Figure 21 Final fish barrier design #3 - Erosion pattern after operating model at 30,000 ft^3/s.

Figures 10 through 19 show the final design (Barrier #3) operating during test flows at 5,000 ft^3/s and above, where the flow pattern has gone through a transition. Velocities exiting the end of the roller bucket are now high enough to project the jet away from the barrier, thus pulling materials upstream where they build up next to the downstream face of the bucket, adding some stability to the barrier. So although erosion depths become substantially greater at higher discharges, the danger of undermining the structure decreases significantly. Figures 20 and 21 show the erosion pattern after the model was run for an hour at 10,000 ft^3/s and 30,000 ft^3/s respectively. Table 26 shows that as flow increases, scour depths for barriers #1 and #3 increase and move further downstream. However, it is worth noting that for both barrier designs, at 30,000 ft^3/s and 45,000 ft^3/s, scour depths are somewhat skewed because erosion has spread to the end of the sand pit, 10 model-ft downstream from the barrier, where a solid platform is still intact. As a result, once the sand reaches a level below the level of the downstream platform, it is likely that flow recirculation next to the platform unrealistically accentuates scour depths. This is more pronounced with barrier #3 because erosion spread downstream more quickly.

In addition, these tests do not simulate aggradations of material that might be carried downstream over the crest or carried upstream from areas beyond the scour locations. Reclamation's Sedimentation and River Hydraulics group (86-6840) should be able to provide additional information and potential prototype scour depths for a more quantitative assessment.

Table 26. Sand scour depth after running for 2.24 hours (prototype).

Prototype Discharge (ft^3/s)	Barrier Design #3		Barrier Design #1	
	Sand Depth (ft)	Downstream Distance from Barrier (ft)	Sand Depth (ft)	Downstream Distance from Barrier (ft)
200	0.5	0.10	1.25	0.0
600	0.58	0.31	N/A	N/A
1,000	0.58	1.46	1.79	0.0
5,000	1.54	8.21	N/A	N/A
10,000	2.25	12.10	1.50	10.0
20,000	3.71	21.50	2.50	16.0
30,000	5.29	27.0	3.50	19.5
45,000	7.50	28.0	4.0	28.8

Conclusions

Barrier design #3 was the only design tested that met either surface drop criteria and/or velocity criteria for all flow conditions tested. Therefore, fish barrier design #3 was accepted as the final design.

Surface drop criteria for design #3 was met for flows up to 1,000 ft^3/s and velocity criteria was met for flows of 1,000 ft^3/s and above. This overlap in meeting both criteria brings an added level of confidence in achieving acceptable performance throughout the range of flow conditions expected at the barrier. In addition, shallow flow depths over the barrier at flows below 1,000 ft^3/s may serve as an additional deterrent to fish passage over the barrier. As flows increase above 1,000 ft^3/s, turbulence increases in the area within the roller bucket serving as another deterrent to passage by making it difficult or impossible for fish to stage for a jump in this area.

Patterns of erosion documented for barrier design #3 indicate that scour produced downstream from the barrier should not endanger the stability of the structure. However, since a sectional physical model had to be used to represent the barrier, the model performs as if the upstream topography provides uniform approach conditions upstream from the structure. Due to the channel geometry on the Virgin River, upstream from the barrier location, this will not be the case with the prototype structure, especially at the higher flows. Therefore there may be times when flow is skewed and more concentrated to one side. This may reduce overall performance of the barrier and may cause significantly more erosion on one side of the river channel. However, high velocities should continue to keep downstream scour away from the structure. Data from the physical model was provided to Reclamation's Sedimentation and River Hydraulics group to help refine the numerical model for predicting erosion depths. The resulting information from this study should be used in conjunction with the data obtained from the physical model study to more accurately define and assess flow patterns and scour downstream from the structure.

Details for the final design of the barrier are provided in Appendix A. The design provided here only depicts the geometric shape for producing acceptable hydraulic performance and meeting barrier criteria. The structural design for the barrier was not determined from this study and was not included as part of this report.

References

1. U.S. Fish and Wildlife Service, “Virgin River Fishes Recovery Plan”, Department of Interior, March 1985.

2. Bureau of Reclamation, “Design of Small Dams”, Department of Interior, 1987.

3. Peterka, A.J., “Hydraulic Design of Stilling Basins and Energy Dissipaters,” Engineering Monograph No. 25, United States Department of Interior, Bureau of Reclamation, Denver, Colorado, May 1984.

4. HEC-RAS River Analysis System Version 4.1, Developed by the U.S. Army Corps of Engineers, Hydrologic Engineering Center (HEC) 609 Second Street Davis, CA 95616.

Appendix A
Design Details for Final Barrier Design

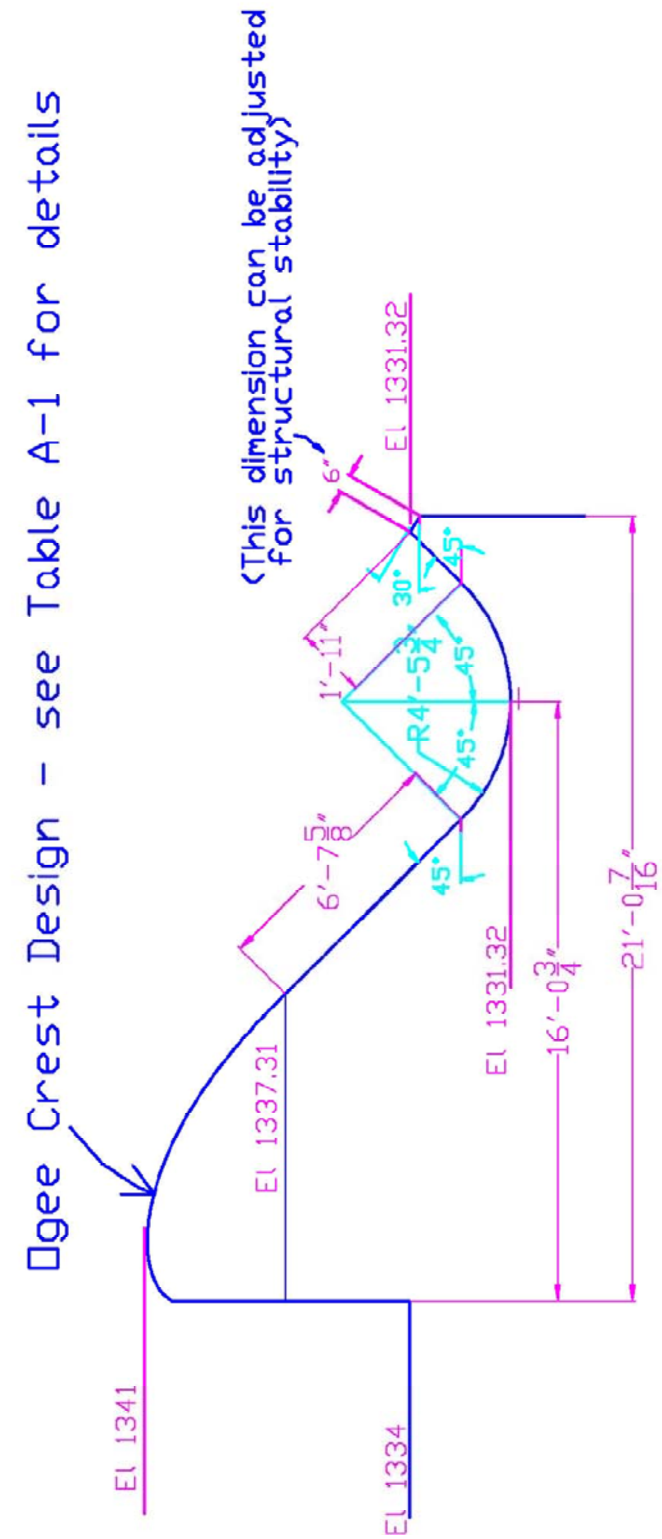

Figure 22. Final fish barrier design for Halfway Wash on the Virgin River.

Table 27 Ogee crest details for final fish barrier design.

Ogee Crest Shape Data	
X- Coordinates (ft)	**Y- Coordinates Elevation (ft)**
0	1334.000
0	1340.358
0.1	1340.489
0.2	1340.591
0.3	1340.674
0.4	1340.741
0.5	1340.795
0.6	1340.839
0.7	1340.873
0.8	1340.901
0.9	1340.925
1	1340.946
1.1	1340.963
1.2	1340.977
1.3	1340.988
1.4	1340.995
1.5	1340.999
1.6	1341.000
1.7	1340.998
1.8	1340.993
1.9	1340.986
2	1340.977
2.1	1340.966
2.2	1340.953
2.3	1340.938
2.4	1340.922
2.5	1340.904
2.6	1340.883
2.7	1340.862

X- Coordinates (cont) (ft)	Y- Coordinates (cont) (ft)
2.8	**1340.838**
2.9	**1340.813**
3	**1340.786**
3.1	**1340.757**
3.2	**1340.727**
3.3	**1340.695**
3.4	**1340.662**
3.5	**1340.627**
3.6	**1340.590**
3.7	**1340.552**
3.8	**1340.512**
3.9	**1340.471**
4	**1340.428**
4.1	**1340.384**
4.2	**1340.338**
4.3	**1340.291**
4.4	**1340.242**
4.5	**1340.192**
4.6	**1340.140**
4.7	**1340.087**
4.8	**1340.032**
4.9	**1339.976**
5	**1339.918**
5.1	**1339.859**
5.2	**1339.798**
5.3	**1339.736**
5.4	**1339.673**
5.5	**1339.608**
5.6	**1339.542**
5.7	**1339.474**
5.8	**1339.405**
5.9	**1339.334**
6	**1339.263**
6.1	**1339.189**

X- Coordinates (cont) (ft)	Y- Coordinates (cont) (ft)
6.2	**1339.115**
6.3	**1339.038**
6.4	**1338.961**
6.5	**1338.882**
6.6	**1338.802**
6.7	**1338.721**
6.8	**1338.638**
6.9	**1338.553**
7	**1338.468**
7.1	**1338.381**
7.2	**1338.292**
7.3	**1338.203**
7.4	**1338.112**
7.5	**1338.019**
7.6	**1337.926**
7.7	**1337.831**
7.8	**1337.734**
7.9	**1337.637**
8	**1337.538**
8.1	**1337.437**
8.22	**1337.313**