COMPOSITE MODELING OF THE HALFWAY WASH FISH BARRIER

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BACKGROUND

The lower Virgin River in Southeast Nevada is home to two native fish species currently listed as endangered. These fish populations are under threat due to the upstream invasion of non-native fish from Lake Mead. The Virgin River Fishes Recovery Plan outlines the steps necessary to recover the endangered fishes, calling for the construction of fish barriers on the river. 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 re-introduced. The barrier then prevents future invasion of non-native species, allowing the native fish populations to rebound.

INTRODUCTION

The Bureau of Reclamation was tasked with designing an effective fish barrier on the lower Virgin River in an area referred to as Halfway Wash; approximately 16 miles upstream of Lake Mead in the northwest corner of Arizona. A project location map is shown in Figure 1. This structure will be the most downstream structure on the lower Virgin River. The barrier is to be located where the river valley consists of a wide, relatively flat floor bounded by steep canyon walls. The valley floor is about 1,600 feet wide with a maximum elevation change of about 10 feet across its width. Only during very large flood events does the river occupy the entire width of the river valley.

A composite set of models, each at varying spatial scales, was utilized to propose a fish barrier design concept that would optimize its use as a deterrent to non-native fish passage while minimizing erosion immediately downstream of the structure. Composite modeling is when numerical models are used in conjunction with physical modeling to obtain more detailed information (Rahmeyer et al., 2011). Each modeling technique has its own sets of uses and limitations. Therefore, the collaborative results from the concurrent use of multiple models allowed for a more accurate and thorough analysis of the proposed barrier.

A geometrically scaled physical model along with two-dimensional (2D) numerical modeling of the local hydraulics and sediment were employed to achieve project goals. The project goals, besides limiting the passage of non-native fish species, were to assess the barrier effectiveness through evaluating local hydraulics at various discharges of interest and structure stability through determining the scour and aggradation effects of the barrier. The physical model was used to optimize the fish barrier design while verifying that design criteria were met and evaluating potential scour immediately downstream of the structure. The Sedimentation and River Hydraulics Two-Dimensional (SRH-2D) numerical model was used to evaluate the overall effect the structure would have on the surrounding area hydraulics as well as predict the erosion patterns downstream of the structure, which was accomplished through the use of two separate modules; the first being fixed bed hydraulics and the second being mobile bed sediment transport. Together, this suite of modeling techniques allowed for the development and comprehensive evaluation of an effective fish barrier.

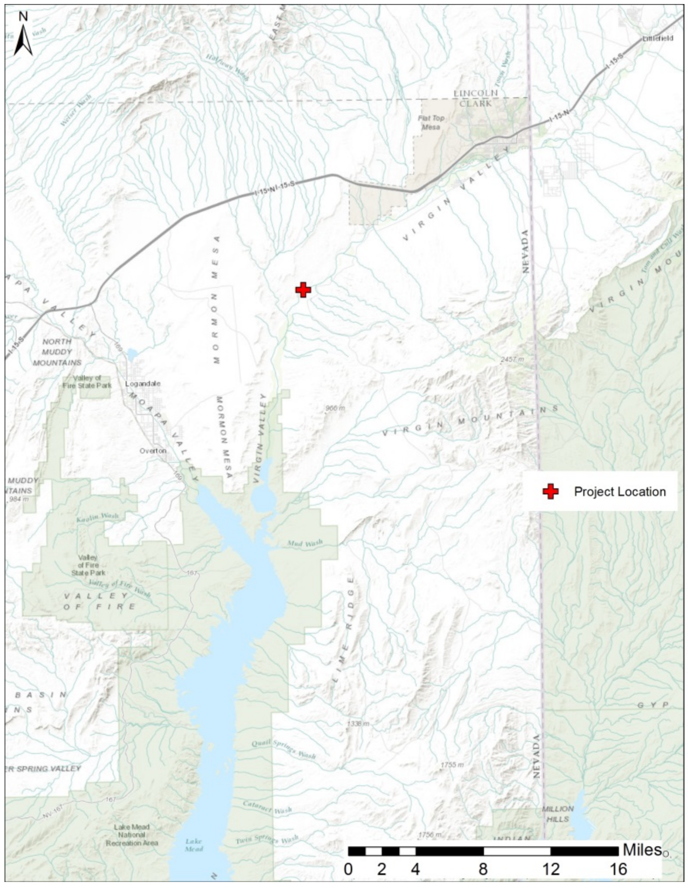

Figure 1 Project location map.

PREFERRED DESIGN ALTERNATIVE

The primary purpose of the fish barrier was to create enough of a vertical discontinuity and increases to in-stream velocities to prevent the upstream passage of invasive, non-native fishes. At low flows, the barrier will create a vertical discontinuity in the stream surface that the fish will not be able to jump over. At high flows, the barrier will be partially submerged and the vertical discontinuity will not develop, but the stream velocity will be above the highest dash speed of the fish. At intermediate flows, the barrier will produce a combination of vertical discontinuity and high stream velocities that will prevent fish passage. The Bureau of Land Management (BLM) provided Reclamation with design requirements that the barrier create a minimum 5 foot tall vertical discontinuity and increase the stream velocities to at least 11.5 ft/s whenever the vertical discontinuity criterion was not met.

The design flow for the structure was given as 45,000 ft^3/s. However, flows in the river are more often in the range of 100-to-5,000 ft^3/s. Therefore, the barrier had to be designed to perform well throughout this full range of flow conditions. An ogee shaped crest is generally considered the most efficient design for passing large flood events and was chosen for the design.

The next question that had to be addressed was how to maximize energy dissipation while also providing an upstream fish deterrent for this range of flow conditions. 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 roller bucket produces extreme turbulence in the localized area at the toe of the structure where the 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 fish to stage for a jump at that location.

Utilizing the ogee crest and roller bucket concepts, a physical model study was completed by Reclamation's Hydraulic Investigations & Laboratory Services Group, evaluating several design iterations in ultimately determining the preferred barrier design that was deemed the most effective for meeting all design criteria (Hanna and Lentz, 2012). The outline of the preferred design alternative is shown in Figure 2.

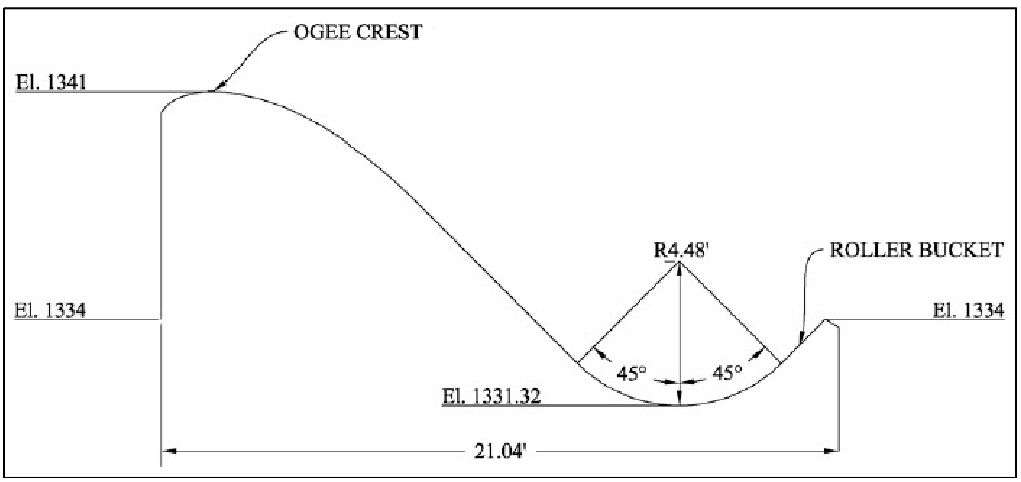

Figure 2 Preferred design alternative of the Virgin River fish barrier (prototype dimensions and elevations).

MODELING METHODOLOGY

All models require simplifying assumptions and thus have limitations. The choice of model is often governed by time and budget constraints, access to and knowledge of existing models, and the ability to develop the model (data availability). It is important to understand the formulation of the selected model, recognize the model limitations, and apply the model in a manner that takes advantage of its strengths. Model predictions will always include some uncertainty because the physical processes being modeled are not completely represented.

A composite suite of models was utilized to evaluate both the stability and predicted effects the proposed fish barrier will have on the river system. A physical model was used to optimize the fish barrier design while verifying that design criteria were met and evaluating potential scour immediately downstream of the structure (Hanna and Lentz, 2012). A two-Dimensional (2D) numerical hydraulics and sediment transport model was used to evaluate the overall effect the structure would have on the surrounding area hydraulics as well as predict the erosion patterns surrounding the structure and scour downstream of the structure (Russell and Sixta, 2012).

Physical Model: Due to such a large width of the river channel and the wide range of flow conditions to be tested, a 1:5 geometric scale sectional physical model was used to represent the structure (Hanna and Lentz, 2012). The width of the barrier inside a 4-foot wide testing flume represented a 19.75 foot slice of the prototype barrier. Froude similitude was used to establish a kinematic relationship between the model and the prototype. Sand was placed downstream of the barrier to evaluate local scour depths and erosion patterns. This was a qualitative evaluation relative to each subsequent design given that the river channel is made up of silts and sand and not possible to be accurately represented geometrically in the model using Froude similitude. The layout of the physical model is shown in Figure 3.

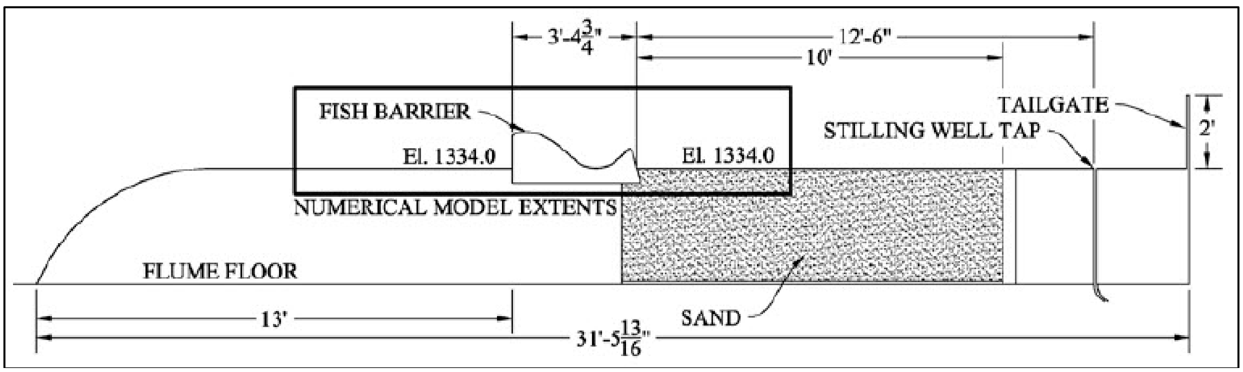

Figure 3 Physical model layout (dimensions in model scale, elevations in prototype scale).

Tailwater depths in the model were set to match depths determined from a one-dimensional HEC-RAS model of the Virgin River. Upstream depths were measured 4 model-feet upstream from the barrier crest. Downstream depths were measured 12.5 model-feet downstream from the roller bucket. Other water surface measurements and velocities were taken along the length of the structure to determine if design criteria were properly met. Model flow rates were measured using calibrated venturi meters.

Two-Dimensional (2D) Numerical Model: SRH-2D is a two-dimensional (2D) hydraulics and sediment transport (mobile-bed) model for river systems developed by Reclamation at the Technical Service Center (Lai, 2008). SRH-2D solves the depth-averaged dynamic wave equations with a depth-averaged parabolic turbulence model using a finite-volume numerical scheme. The model adopts a zonal approach for coupled modeling of channels and floodplains; a river system is broken down into modeling zones (delineated based on natural features such as topography, vegetation, and bed roughness), each with unique parameters such as flow resistance. One of the major features of SRH-2D is the adoption of an unstructured hybrid mixed element mesh, which is based on the arbitrarily shaped element method of Lai (2000) for geometric representation. This meshing strategy is flexible enough to facilitate the implementation of the zonal modeling concept, allowing for greater modeling detail in areas of interest that ultimately leads to increased modeling efficiency through a compromise between solution accuracy and computing demand.

The SRH-2D modeling was broken up into two distinct efforts (Russell and Sixta, 2012). Fixed bed, hydraulic conditions were first modeled; to determine an appropriate model extent (primarily width), to perform a flow roughness calibration, and to obtain hydraulic model results to address some of the study questions. Modeling of the mobile channel dynamics and sediment transport commenced after a satisfactory hydraulics model was constructed and calibrated.

Due to the increased computational demand for the mobile-bed modeling, separate meshes/model domains were generated using Surface-water Modeling System (SMS) software for the hydraulics and sediment transport modeling. The model domain spanned laterally valley wall-to-valley wall and longitudinally 0.9 river miles upstream and 2.0 (hydraulics) and 0.9 (mobile-bed) river miles downstream of the fish barrier. A total of 56,500 and 21,000 mixed quadrilateral/triangular elements were used to represent the model domain for the hydraulics and sediment transport modeling, respectively. In each mesh, the resolution was denser (~5X; longitudinal spacing) at the fish barrier in order to better capture its geometry as it was a feature of focus.

A combination of several data sets was used to construct the topography of the study area. Ground survey data were collected upstream and downstream of the proposed fish barrier before December, 2010 (exact date is unknown) and on June 20, 2011 and July 5, 2011. These data were mainly used to represent the wetted portion of the channel (bathymetry). To supplement the survey data in the floodplain areas, a Digital Terrain Model (DTM) containing elevations of natural terrain features was obtained. The data making up the DTM was collected using airborne Interferometric Synthetic Aperture Radar (IfSAR) technology. The IfSAR data had a 5-meter posting with a published vertical accuracy of +/- 1 meter. The ground survey and IfSAR data were combined to create a representative topographic surface in ArcGIS using a Triangulated Irregular Network (TIN) methodology that each mesh was solved against.

Four distinct roughness zones were used in the model domain; 1) main channel, 2) vegetated floodplain, 3) cleared floodplain, and 4) fish barrier. Delineation of these zones utilized aerial photography in combination with information from the ground survey data. The corresponding material type roughness values used in the modeling were set through an iterative model calibration process. The resultant roughness values were 0.020 for the main channel, 0.045 for vegetated floodplain, 0.025 for cleared floodplain, and 0.013 for the fish barrier. The same roughness coefficients were used for both the hydraulics and sediment transport modeling and all were held constant for the entire range of discharges modeled.

Bed sediment gradations and sediment supply are needed for sediment transport modeling. For this study, uniform surface and subsurface gradations were applied to the entire model domain. Ten (10) geologic test pits and three (3) drill holes were excavated near the proposed fish barrier site. Sediment data was measured at each location for multiple depths. Based on that information, a change in bed material was detected at 5 feet of depth. Therefore, sediment gradations were averaged for the top surface layer (less than 5 feet) and subsurface layer (greater than 5 feet). A uniform two layer gradation with 5 sediment size classes was used over the entire model domain due to the small number of samples surveyed. Vertical erosion limits were not set for the subsurface layer. Sediment supply was determined using the Engelund and Hansen (1972) sediment transport formula to calculate capacity, which is the amount of sediment that can be transported while maintaining a stable bed locally.

Seven (7) steady state discharges were simulated in the 2D hydraulics and sediment transport models: 200 ft^3/sec, 600 ft^3/sec, 1,000 ft^3/sec, 5,000 ft^3/sec, 10,000 ft^3/sec, 30,000 ft^3/sec, and 45,000 ft^3/sec. These discharges range from a regularly occurring high flow to a conservative design flow. In addition, three (3) unsteady hydrographs were simulated for the sediment transport modeling. All three hydrographs represented flood flows happening on a less than annual basis. The hydrographs represented the 1995 flood, a high flow flood, and a scaled synthetic design flow flood to peak at 45,000 ft^3/sec. The hydrographs have duration of less than 12 days. For the unsteady flow simulations, the annual peak stream flow and average daily stream flow at the nearest USGS gage (Virgin River at Littlefield, AZ 09415000) were used to determine the magnitude and shape of storm hydrographs for the Virgin River in the project area. The only time flow was above the largest design flow under consideration (45,000 ft^3/sec) was in 1989 when there was a dam break upstream.

MODEL RESULTS DISCUSSION

Physical Model: Three (3) designs were evaluated with the physical model before settling on one that met either the surface drop and/or velocity criteria for all flow conditions tested. For each test condition, depth measurements along the barrier were taken through the flume glass sidewall, perpendicular to the urethane surface at 0.5-to-1.0 foot incremental drops in elevation until the determined tailwater surface was reached. Measured depths were used to calculate average velocities flowing over the barrier at each location. Velocities were also measured using a Swoffer propeller meter at the model centerline when flow depth was adequate. These velocities were not averaged over the full flow depth, so in most cases the readings are higher than the average velocity calculated using the depth measured near the same location.

Surface drop criteria for the preferred alternative design was met for flows up to 1,000 ft^3/sec and velocity criteria was met for flows of 1,000 ft^3/sec and above (Table 1). 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.

Table 1 Measured stream surface drop and velocity for preferred alternative design.

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

Although actual scour depths could not be simulated due to scaling issues, the patterns of erosion that would occur could be reasonably represented in the physical model using fine sand. Therefore, erosion measurements were conducted to get qualitative data on resulting erosion patterns relative to each test. The 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. Table 2 shows the scour depths and corresponding distance for each flow rate tested for the preferred alternative design. Results show that as flow increases, maximum scour depths increase and move further downstream. For flows up to 1,000 ft^3/sec erosion occurs close to the downstream edge of the barrier. Erosion occurs next to the structure with low discharges because velocities are low, and therefore flow at the end of the roller bucket tends to drop vertically downward over the downstream edge resulting in erosion in close proximity to the barrier, but also not very deep. At flows of 5,000 ft^3/sec and above, the flow pattern appeared to go through a transition. The patterns of erosion indicated that scour produced downstream from the barrier should not endanger that stability of the structure. However, it's important to note that the structural design for the barrier was not determined from this study.

Table 2 Scour depths and corresponding distance for preferred alternative design.

Prototype Discharge (ft^3/s)	Barrier Design #3	
	Sand Depth (ft)	Downstream Distance from Barrier (ft)
200	0.5	0.10
600	0.58	0.31
1,000	0.58	1.46
5,000	1.54	8.21
10,000	2.25	12.10
20,000	3.71	21.50
30,000	5.29	27.0
45,000	7.50	28.0

Two-Dimensional (2D) Numerical Model: As mentioned previously, the 2D numerical modeling was broken into two separate efforts; fixed-bed hydraulics modeling and mobile-bed sediment transport modeling. The main objective of the hydraulics modeling was to quantify differences among the currently existing and proposed conditions over a range of flow conditions. The predicted hydraulic parameters of interest included flow depth, water surface elevation, and velocity magnitude and direction. The spatial distributions of these parameters were examined to determine the location and magnitude of the differences between the existing and proposed conditions, which were used to forecast project impacts. This was accomplished by differencing raster grids representing the specific model hydraulic parameters in ArcGIS.

The spatial distribution of the differences in water depths near/around the fish barrier for the 45,000 ft^3/sec event is shown in Figure 4. Results show an overall increase in depth upstream of the fish barrier and decrease in depth downstream of the barrier. The relative magnitudes of depth decreases downstream of the barrier are small as compared to the depth increases upstream of the barrier; the biggest differences occur within close proximity of the barrier. The results also show the barrier to back water upstream approximately 0.4 miles.

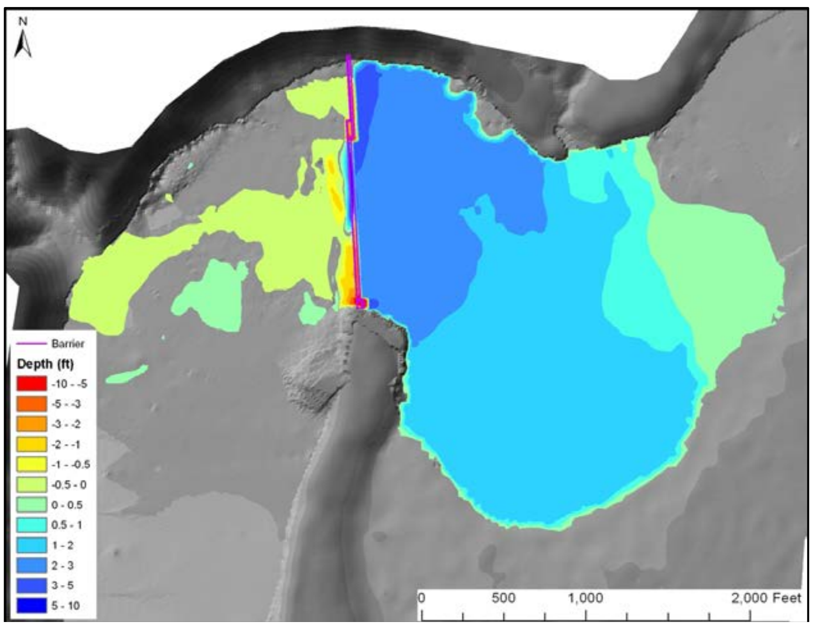

Figure 4 Depth difference (proposed – existing) for the 45,000 ft^3/sec event.
(Flow is from right-to-left).

Resultant velocity magnitude and vectors for the 45,000 ft^3/sec event with the proposed barrier showed flow to be distributed along the entire barrier, but not with a consistent magnitude. Velocities were seen to be larger along the southern portion of the barrier. The average velocities for the 45,000 ft^3/sec event just upstream of the barrier ranged from 6-8 ft/sec, while the average velocities just downstream of the barrier ranged from 7-9 ft/sec on the northern half, and 12-18 ft/sec on the southern half. (These velocities can be compared against the design criteria of 11.5 ft/s. However, it's important to keep in mind that they refer to the velocities in the main channel and not on the barrier itself). Furthermore, the velocity vectors showed slower recirculation zones on the northern end of the barrier on both the upstream and downstream sides.

Sediment transport modeling was used to predict the erosion/deposition patterns near/around the structure. The first set of mobile-bed simulations used a constant, steady flow that was carried out for 10 days for both the existing and proposed barrier conditions. The net change in bed elevation, relative to the initial bed at time zero is shown in Figure 5 for the design event (45,000 ft^3/sec). Based on results from all of the steady flow runs, the following conclusions were made:

- At 200 ft^3/sec there is little change to the bed elevation for both the baseline and barrier conditions; flow must be greater than 200 ft^3/sec to move appreciable amounts of sediment within the system.
- For the baseline condition, erosion occurs along the south valley wall. There is potential for the river planform to shift toward the south and straighten under this condition.
- For the proposed condition, erosion will occur downstream of the barrier and it appears likely that the river planform will shift to the south and straighten (similar to the baseline condition). The model does not include the differences in potential erodibility of cleared versus vegetated areas on the banks and floodplain. Although all of the simulations above 10,000 ft^3/sec show this planform change, it may be a slow developing process.
- For the proposed condition, the backwater upstream of the barrier creates a net depositional area. However, there is some local scour in certain places. Most notably a bar develops on the south side of the channel which concentrates the flow in the north portion. Local scour occurs where the flow is concentrated.
- For the proposed condition, it is likely that alternating bars will form upstream until the river is out of the barrier backwater influence. This process will likely develop slowly and will depend on the amount of time and frequency that the river discharge is greater than 200 ft^3/sec.
- In the proposed condition, bank erosion may be an issue where the flow is concentrated upstream of the barrier. The sediment transport model does not include bank erosion, but it is likely that the right bank upstream of the barrier will experience some bank erosion.
- Immediately downstream of the barrier, erosion occurs. However, this erosion does not include plunging scour off of the barrier roller bucket and is potentially under predicted. Further downstream the erosion represents the reach average scour.

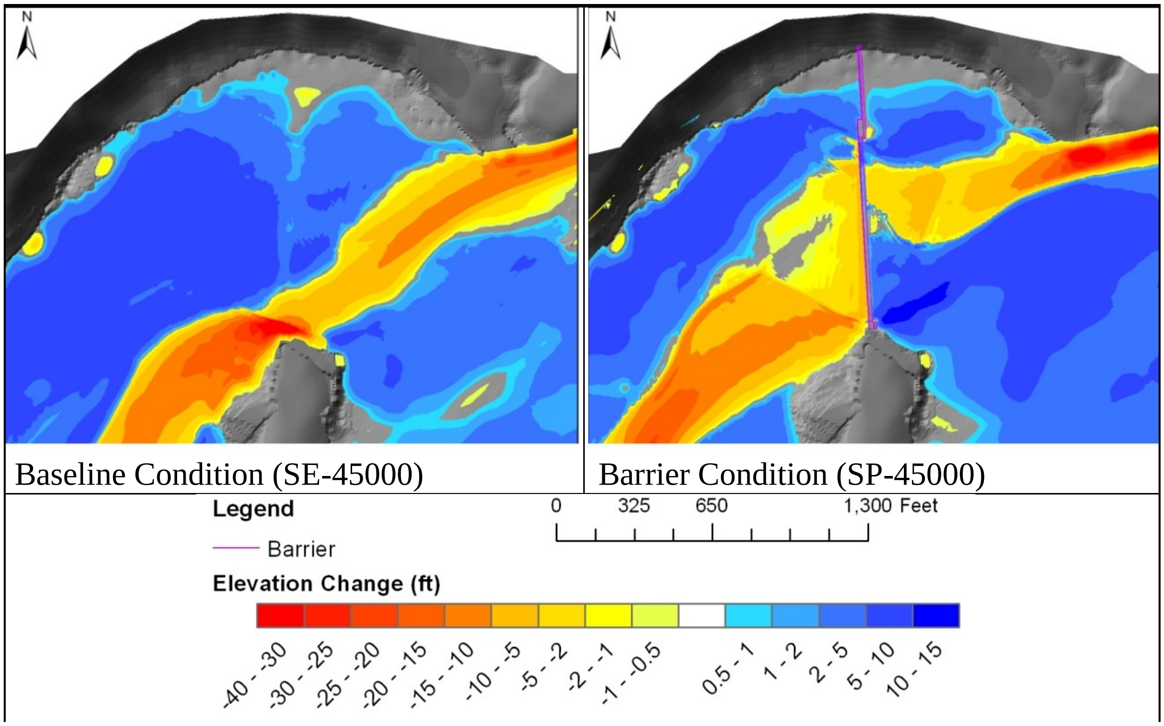

Figure 5 Change in bed elevation for existing and proposed conditions at 45,000 ft^3/sec. (Flow is from right-to-left).

Based on the flow record, high steady flows are unlikely to occur at this location. As a result, the prolonged steady flow simulations were viewed as a conservative estimate of the erosion that will occur in the study reach. Three unsteady hydrographs were simulated to provide a more realistic prediction of the erosion and deposition patterns. The evolution of the bed elevation throughout the simulations were evaluated and seen to produce similar erosion and deposition patterns although the magnitude of bed change varies. Deposition occurs upstream of the barrier in all three scenarios. For the 45,000 ft^3/sec peak hydrograph, a deeper main channel is eroded. This is similar to the steady flow results where the flow was concentrated upstream of the barrier due to bar development.

Downstream of the barrier, there is a pocket of increased erosion that occurs on the north abutment in all three hydrographs. Erosion did occur in this location during the steady flows but the magnitude was less. As expected, further erosion occurs downstream of the barrier. One of the most noticeable differences between the 45,000 ft^3/sec steady flow and the 45,000 ft^3/sec hydrograph is that during the steady flow simulation, deposition occurs downstream of the barrier on the left and right banks; a single thread main channel is clearly defined. However, for the hydrograph simulation, the majority of the downstream valley bottom is degraded. It appears that the channel has started to straighten and shift towards the south. Figure 6 shows the net eroded/deposited depth, relative to the initial bed at time zero for the last time step (t = 11 days) of the 45,000 ft^3/sec simulation. The river channel has started moving towards the planform shown in the steady flow runs, but was unable to completely develop and shift its alignment.

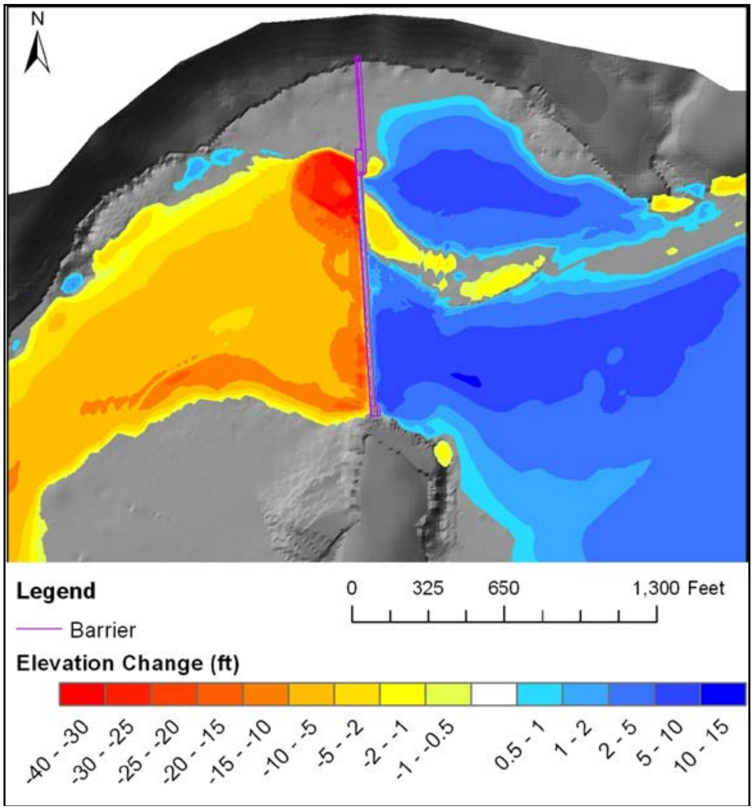

Figure 6 Change in bed elevation for the final time step (t= 11 days) for the synthetic 45,000 ft^3/sec peak hydrograph.

The 2D sediment transport numerical model cannot predict local scour due to the inability of quantifying plunging flow, but it can predict the decrease in river bed elevations due to the reduction in sediment load caused by the structure and larger discharges. Therefore, the 2D model was used to estimate the "reach average" erosion. The reach average erosion is that erosion that occurs over a large spatial scale and is relatively uniform in the streamwise direction. The reach average erosion was approximately 20.5 feet, which was considered the maximum total bed scour that the fish barrier's foundation should be designed around. However, it's also worth keeping in mind the scour findings from the physical modeling showing that as flow increases, maximum scour depths increase, but also move further downstream.

SUMMARY AND CONCLUSIONS

The Bureau of Reclamation was tasked with designing an effective fish barrier on the lower Virgin River in an area that is referred to as Halfway Wash. The barrier is designed to prevent upstream non-native fish passage by creating a vertical discontinuity in the river that fish are unable to jump over as well as increasing the stream velocities above the maximum dash speed of the fish. A composite of models, each at varying spatial scales, was utilized to propose a fish barrier design concept that would optimize its use as a deterrent to fish passage while minimizing erosion immediately downstream of the structure. Each modeling technique has its own sets of uses and limitations. Therefore, the collaborative results from the concurrent use of multiple models allowed for a more accurate and thorough analysis.

Scaled physical modeling along with 2D numerical modeling of local hydraulics and sediment were employed to achieve project goals of preventing fish passage while maintaining structural stability of the feature preventing fish passage. An ogee crest with roller bucket concept was used in the design of the fish barrier. The physical model showed a design that met both drop height and velocity design criteria with an overlap of discharges. Patterns of erosion showed that as flow increases, maximum scour depths increase and move further downstream of the barrier. The 2D hydraulics modeling showed non-uniform velocities upstream and downstream of the barrier, and that the barrier will back water upstream approximately 0.4 miles during the 45,000 ft^3/sec design flow. The 2D sediment modeling showed that flow must be greater than 200 ft^3/sec to move appreciable amounts of sediment within the system. The backwater upstream of the barrier was seen to create a net depositional area with some local scour in areas where the flow is concentrated. Erosion occurs immediately downstream of the barrier. Further downstream the erosion represents the reach average scour, which was approximated to be 20.5 feet. Together, this suite of modeling techniques allowed for the development and comprehensive evaluation of an effective fish barrier.

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