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Managing Water in the West

Hydraulic Laboratory Report HL-2010-02

Blue River Fish Barrier Hydraulic Model Study

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Services Group
Denver, Colorado

March 2012

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14. ABSTRACT
A physical hydraulic model study was conducted on a proposed fish barrier weir for a remote site on the Blue River in eastern Arizona. The study evaluated the hydraulic characteristics of flow over the fish barrier and the resulting scour erosion at flows up to a 100-yr event. The study was used to improve the design of the structure to minimize scour and facilitate construction, since all construction equipment and non-local materials will need to be airlifted to the site.

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Blue River Fish Barrier Hydraulic Model Study

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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

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

This model study was funded by the Bureau of Reclamation's Phoenix Area Office. Thanks for the technical oversight and peer review that was provide by Tony Wahl and Brent Mefford. Thanks to the Bureau of Reclamation's Laboratory Shops for their hard work in constructing the physical model.

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Disclaimer

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BACKGROUND

The Bureau of Reclamation has proposed construction of a fish barrier on the Blue River approximately 13 miles northeast of Clifton, AZ. The barrier will be located on the Blue River approximately 0.5 miles upstream of its confluence with the San Francisco River. The purpose of the proposed fish barrier is to protect populations of loach minnow and Chiricahua leopard frog that reside in the Blue River drainage against future upstream incursion of nonnative aquatic organisms from the San Francisco River. The action is also needed to remove the threat posed by nonnative fishes that already occupy lower reaches of the Blue River. These non-native fishes moved into the watershed following the construction of the Central Arizona Project, which has brought water from the Colorado River into central Arizona.

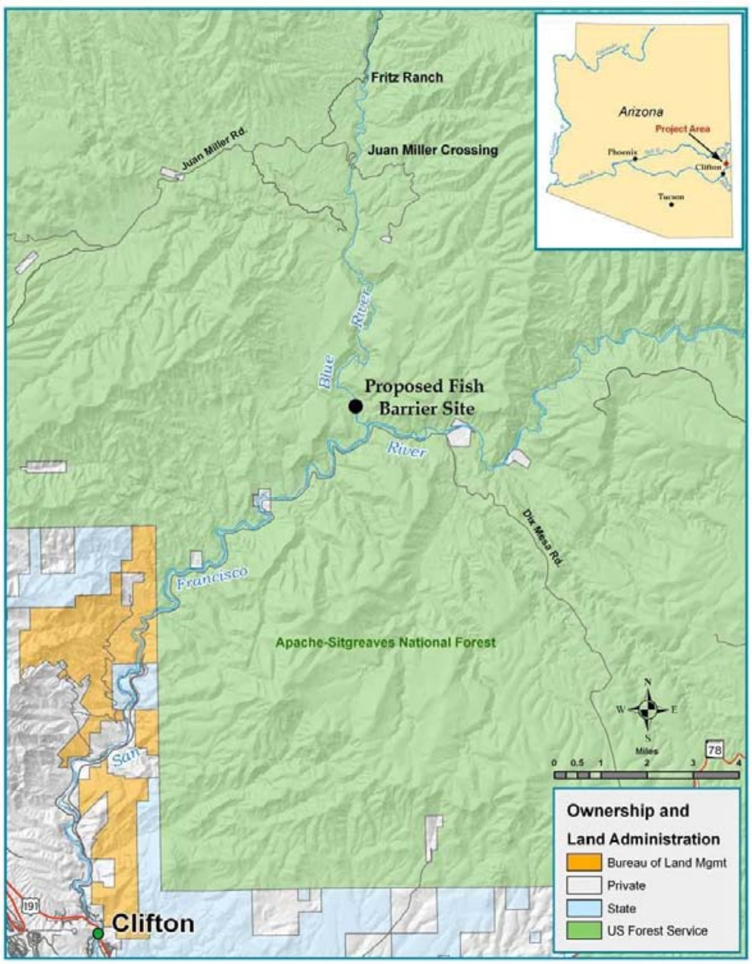

Figure 1. Project Area.

The selected location for the barrier is very remote, approximately 7 miles from the end of the nearest maintained road. All nonlocal construction materials and all construction equipment will be airlifted to the site. There will be minimal opportunity for post-construction maintenance of the site. To optimize the design and ensure reliable long-term performance, a physical hydraulic model study was commissioned for the proposed fish barrier.

Figure 2. Satellite photo showing location of proposed Blue River fish barrier.

THE MODEL

Model Study Objectives

The purpose of the model study was to evaluate the proposed fish barrier for scour erosion that might threaten the stability of the structure or require future maintenance at the site. This included optimizing a deflection block meant to minimize scour, the slope of the downstream scour wall (initially 2:1 [h:v]), and a training wall on the left side of the barrier. Local scour downstream from the barrier was evaluated at discharges corresponding to 2-, 25-, and 100-yr flood return periods.

Table 1. Stream flows for the Blue River near the proposed fish barrier.

Return Period	Discharge ft^3/s
Mean Daily	335
2 Year	2,609
25 Year	19,731
100 Year	35,661

Figure 3. Blue River Fish Barrier- Configuration 3.1 operationg at 100-yr discharge, Q=35,661 ft^3/s.

Model Description

A physical hydraulic model was constructed at Reclamation's Hydraulics Laboratory in Denver, Colorado (Figure 3).

A geometric scale of 1:28 was used to construct the model, which included the fish barrier, about 650 ft of upstream river channel and about 550 ft of downstream river channel. 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 $L_r = 1:28$

Velocity ratio $V_r = L_r^{1/2} = 1:5.29$

Discharge ratio $Q_r = L_r^{5/2} = 1:4149$

The extents of the model are shown in Figure 4. Inflow to the hydraulic model was routed through the pipe chase surrounding the perimeter of the laboratory and was measured by the calibrated laboratory venturi meter system. Water surface elevations were measured using point gages located near the entrance and exit of the model. In addition, the water surface just upstream from the barrier was measured using a point gage in a stilling well. A sediment trap was built at the exit of the model to capture material that was washed out of the model.

The design of the fish barrier is a 4 foot drop onto a 20 foot apron. This produces a high velocity, shallow flow on the apron. Upstream fish passage is further inhibited by a 4 foot vertical jump that must be made from the apron. The barrier is set at an elevation that causes the apron to be 0.5 ft higher than the existing downstream ground surface. For the barrier to work correctly the apron must not be submerged by tailwater. The model fish barrier was constructed from high-density polyurethane, marine plywood and concrete. It was assumed that there would be no scour upstream from the structure, so concrete was used to construct the model topography upstream from the structure. This assumption was confirmed by a numerical sediment model (Russell 2010). Topographic contours were developed from a 1-m digital terrain model (DTM) derived from satellite imagery and adjusted as necessary to reflect the presence of very steep canyon walls and other local topographic features that were not accurately represented in the DTM.

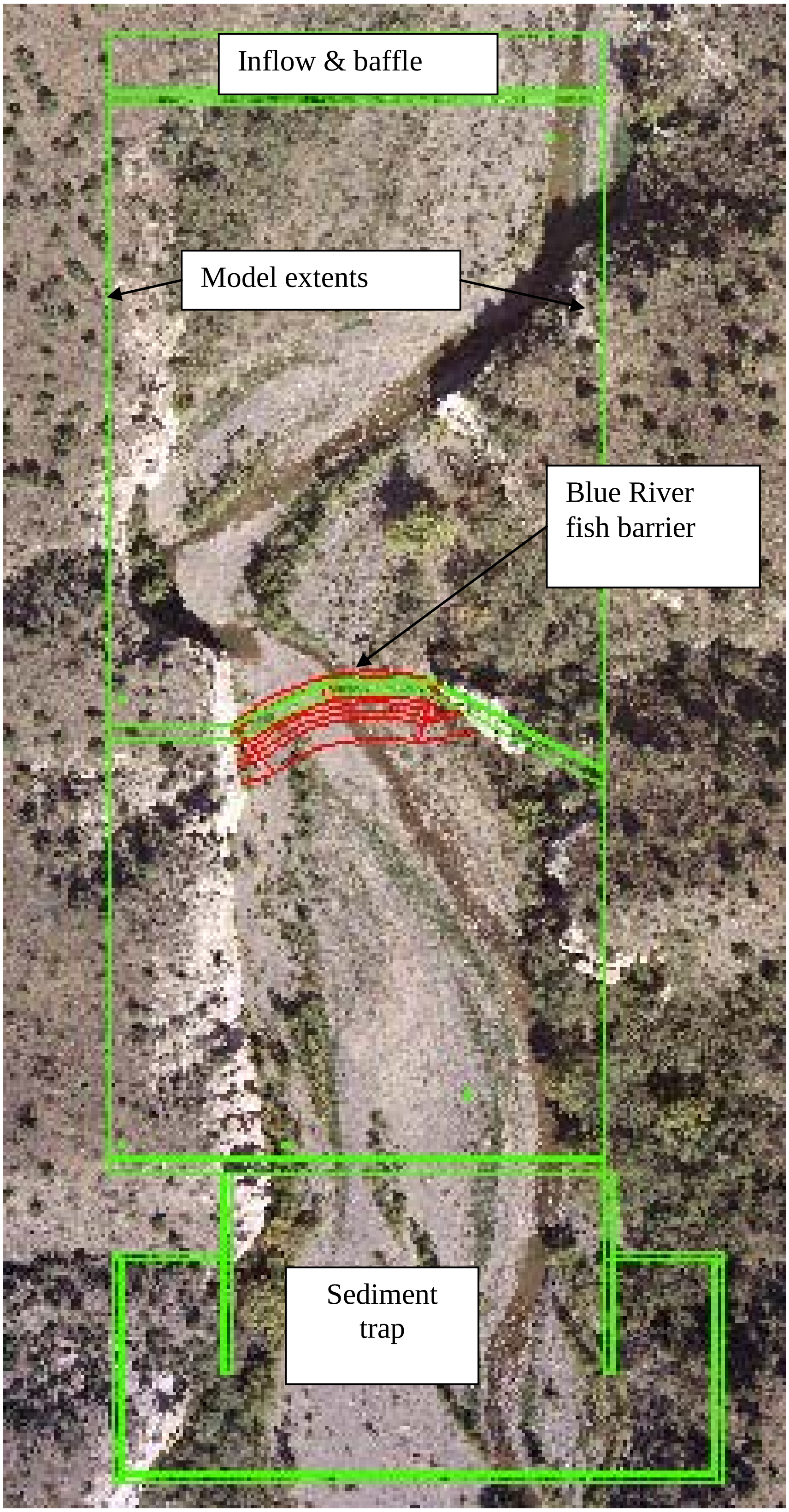

Figure 4. Model extents.

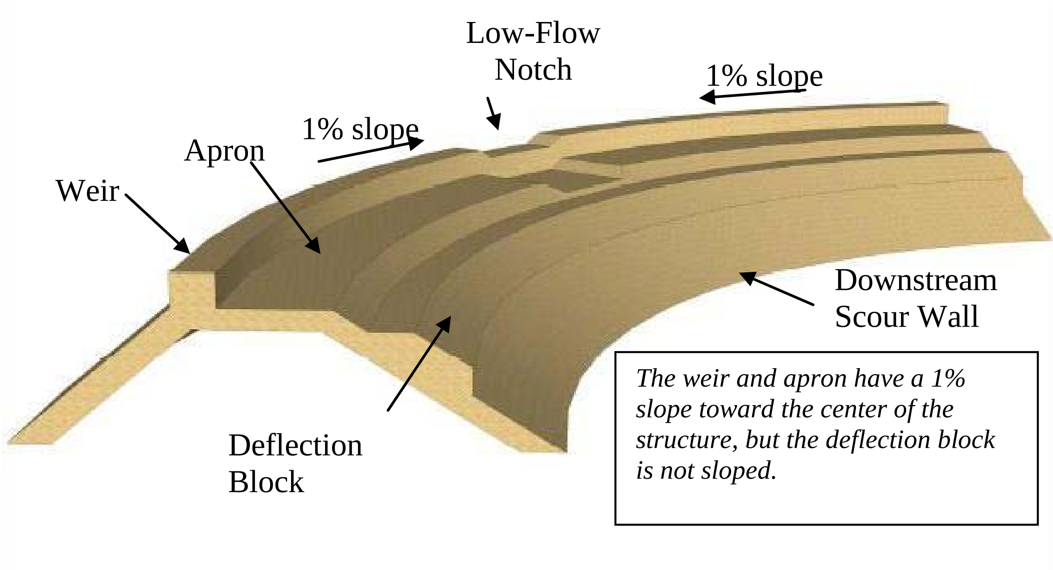

Figure 5. 3-D rendering of the fish barrier initial design.

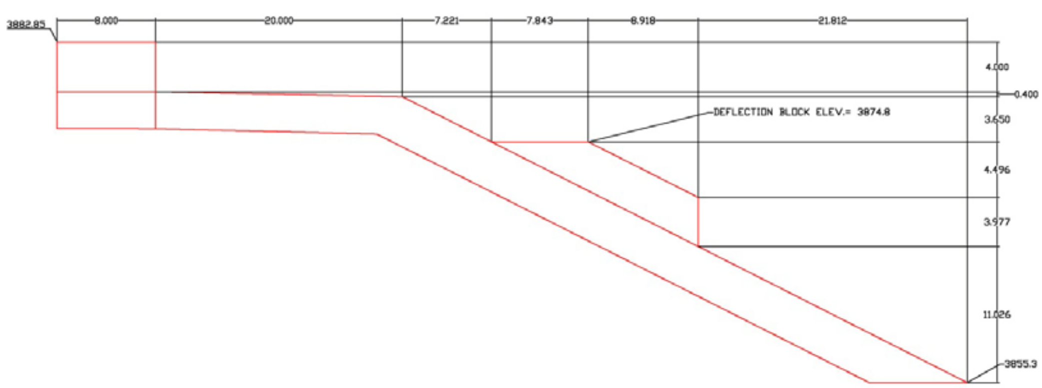

Figure 6. Cross section at side of barrier- initial design.

The initial design called for the sloped downstream scour wall to extend 20 ft below the existing ground surface at a 2:1 slope to an elevation of 3855.3 ft. Site geology shows that the river bed is composed of a very deep alluvium material. In the model, the river channel downstream from the structure was modeled with a movable sand mix that allowed for scour down to elevation 3848 ft. For construction purposes a nonerodible floor was placed in the model at elevation 3848. Cross section templates were used to place sand in the model to form the existing topography. In most cases the sand was reset to this initial topography before a scour test was performed.

An average gradation for the alluvium material at the site was estimated based on 2 test pits and 2 pebble counts. The prototype gradation was scaled down based on the settling velocity of the particles (Figure 7) to arrive at a model sand gradation. In this model study, for particles larger than the prototype d_{50} (37 mm), scaling based on setting velocity was the same as the geometric scaling. Logs from the test pit investigations reported 15% cobbles by volume and occasional boulders up to 24-inch diameter, but the model material gradation did not fully represent this coarsest fraction of the prototype material. In addition, the prototype materials that would have geometrically scaled to fines were also essentially eliminated from the model gradation, since the behavior of fines (cohesion, plasiticity) in the model would not be representative of prototype material behavior. All model runs were clear water tests, meaning the water entering the model was clear and no sediment load was introduced into the model. During each test the material naturally separates, so sand caught in the sediment trap was remixed before being replaced in the model in preparation for the next test.

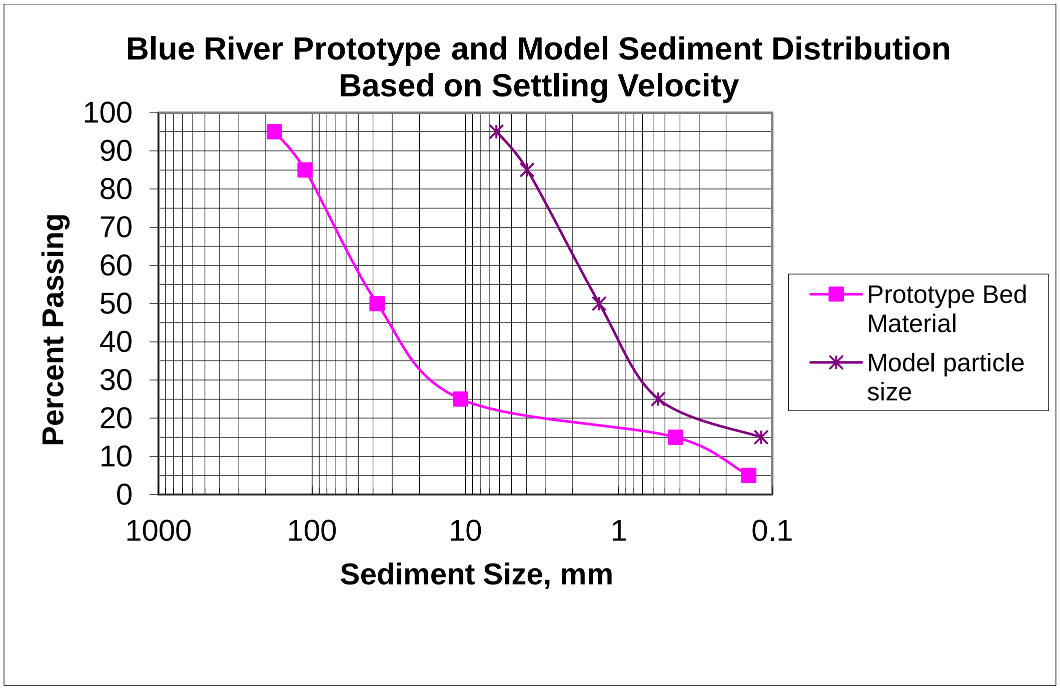

Figure 7. Blue River Prototype and Model Gradations.

A one dimensional numerical flow model was built using HEC-RAS. Cross section data was compiled from a recent survey, a 1-meter digital terrain model (DTM), and an older numerical model. The HEC-RAS model was used to provide water surface elevations for the physical model. Each of the point gages and stilling well were located in the physical model at cross section locations corresponding to sections in the HEC-RAS model. Vertical slat tail boards were used in the physical model to artificially raise the downstream water surface to match the numerical model.

Data Collection

A SonTek FlowTracker® ADV was used to collect velocity data in scour holes downstream from the fish barrier. The 3 dimensional velocity measurements helped to identify the flow patterns that were causing scour.

A 12 megapixel Nikon D700 camera with a 20mm lens was mounted on the top of a 12-ft-high range pole to document sediment erosion and deposition after flow scenarios were run. The photos were processed using ADAM Technology's 3DM CalibCam and 3DM Analyst software. The software produces a Digital Terrain Model (DTM) that can then be used to analyze the riverbed surface. For comparison, a DTM of the initial conditions with topography that matches the prototype existing topography was built. After each test, new photos were taken and a new DTM reflecting the scoured condition was built. Final contour maps and contour maps showing locations of aggradation and degradation were produced.

Limitations

All testing was performed without adding a sediment load to the flow entering the model, and all runs were made with a steady state discharge. In the prototype it is likely that continuous sediment transport through the river reach would reduce the depth of scour downstream from the structure, and some deposition would occur on the falling limb of a natural flood hydrograph. The clear water tests were an attempt to conservatively estimate the maximum possible scour. Tests were continued until it appeared that the scour had reached a stable condition, approximately 50 and 80 minutes for the 100-yr and 25-yr discharges respectively, and model runs were terminated as quickly as possible to preserve the maximum scour condition of the river channel for post-test analysis. Given the modeling methods, the scour observed in the model represents a worst case scenario.

Because of these limitations, the most valuable use of the model results is for comparative evaluation of the scour associated with different design options. Although the model may not accurately predict the exact amount of scour that will occur in the prototype for any given design alternative, the model does provide a good basis for comparing designs and selecting the most desirable design alternatives.

INVESTIGATIONS AND RESULTS

Low-Flow Notch

The initial design incorporated a 2-foot deep low-flow notch in the center of the weir and apron. Ideally this will force the river channel at low flows to the center of the barrier and away from the sides where it might have more potential for erosion at the interface between the abutments and the barrier. The weir and apron also have a 1% slope toward the center of the barrier. Testing showed that at low flows the notch concentrated the flow and caused significant scour directly below the low-flow notch. The mean daily flow and the 2-yr flow showed scour holes 8 ft and 16 ft deep, respectively (prototype depths), as shown in Figure 8.

Figure 8. Scour below the low-flow notch for the mean daily flow (left), and 2-yr flow.

A second series of tests was carried out with the low-flow notch eliminated by filling it in (Figure 9). Without the notch, the flow spread out more and produced very little scour at low discharges. At higher discharges the notch had a minimal impact on scour downstream from the barrier. The 2-ft deep notch in the apron is 0.5 ft above the existing downstream ground surface. It is recommended that the notch be filled in and the entire structure lowered by 2 ft. This would produce similar hydraulic conditions to inhibit upstream fish passage. The vertical drop from the weir crest to the apron would still be 4 ft, but the total drop across the structure would be reduced by 2 ft, leaving less energy available to cause scour downstream from the structure. Tests in which the tailwater level in the model was artificially raised about 2 ft higher than the realistic tailwater level verified that flow across the apron would remain supercritical, so there would be no submergence of the apron.

Figure 9. With the low-flow notch filled in, there was very little scour at the mean daily flow (left) and the 2-yr flow.

Deflection Block

The design purpose for the deflection block (see Figures. 5 and 6) was to prevent the high velocity flow downstream from the barrier from plunging deep into the tailwater pool and causing scour that might threaten the stability of the structure. The initial deflection block's length in the flow direction ranged from 7.8 ft at the abutments to 10.0 ft at the center. At the 100-yr discharge there were 2 different flow conditions observed over the barrier. In the first condition there was a hydraulic jump immediately downstream from the deflection block against the sloped scour wall (Figure 11). This allowed the flow to remain attached to the scour wall and plunge downward toward the riverbed, producing deep scour. A large scour hole across the full width of the structure was formed at the 100-yr discharge. The depth of scour was artificially limited by the floor of the model sand bed (elevation= 3848 ft). Approximately 80% of the structure's scour wall was visible due the lack of sand (Figure 11).

In the second flow condition an undular jet was formed downstream from the barrier. The flow detached from the deflection block and the main jet remained near the water surface instead of plunging down. This condition created a small localized upstream current along the river bottom that moved sand back upstream toward the barrier. This flow condition produced much less scour than the plunging condition (Figure 13).

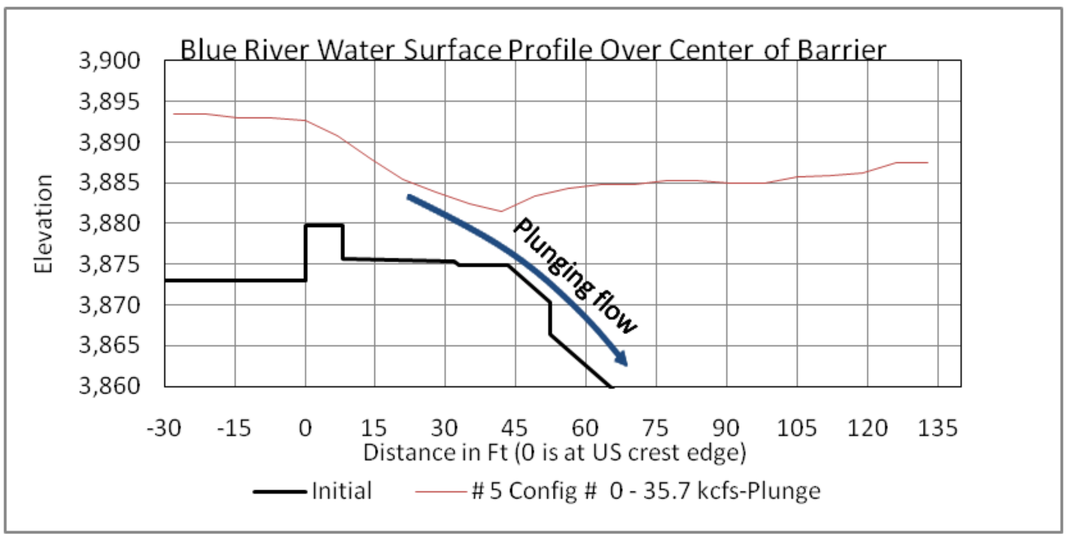

Figure 10. Illustration showing water surface and currents for the 100-yr discharge in a plunging condition.

Figure 11. Plunging flow at the 100-yr discharge (left) for the initial deflection block design. Scour caused by plunging flow (right). Note the exposed false floor of the model at the toe of the sloped scour wall. The deflection block is 8-9 ft long.

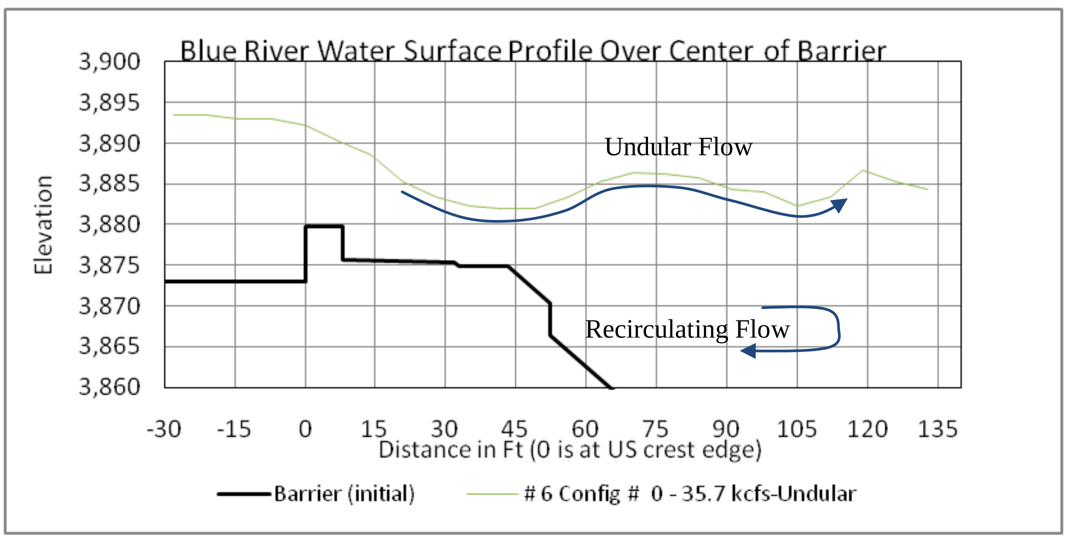

Figure 12. Illustration showing water surface and currents for the 100-yr discharge in a undular condition.

Figure 13. Undular flow at the 100-yr discharge (left) with the initial deflection block design. Scour resulting from undular flow (right). Note the material still in place against most of the scour wall. The deflection block is 8-9 ft long.

During testing of the initial design at the 100-yr event, each of the 2 flow conditions described above were unstable, and the flow would oscillate back and forth during a test. Minor changes in the downstream bed, caused by scour or deposition seemed to drive the oscillation. External flow disturbances would also cause the flow condition to change. For example, one could deflect the flow downward along the sloped scour wall for a few seconds using a piece of wood held in the flow, and the plunging flow condition could be established and would remain in place for several minutes. Given that each condition had very different scour effects, and the plunging flow condition caused very deep scour, this unstable flow pattern was unacceptable. The shape of the deflection block was altered to find a stable condition that produced less scour. In one configuration the deflection block was removed and the scour wall was changed from its initial 2:1 slope to a flatter 4:1 slope. This produced the plunging flow condition that was more stable with the deflection block removed; the result was complete removal of all sand from the downstream face of the structure. The shape of the deflection block that performed the best was a horizontal extension with a length in the flow direction of 16.8 ft at the abutment and 20.0 ft in the center, terminating in an abrupt vertical drop down to the scour wall (see Figure 14). This abrupt end of this block helped the jet to separate from the block and stay near the surface. This shape always produced an undular jet and did not oscillate between the undular and plunging flow conditions. When water surface profiles associated with the different deflection block designs were compared, the extended deflection block produced an undular wave that was longer and flatter than that of the original, shorter deflection block (see Figure 15). There is still scour, but it occurs further downstream, away from the structure.

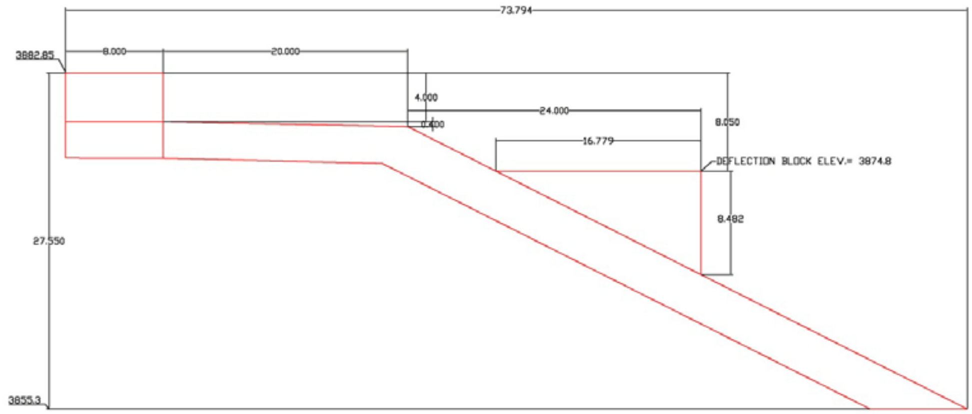

Figure 14. Cross section at side of barrier for recommended configuration.

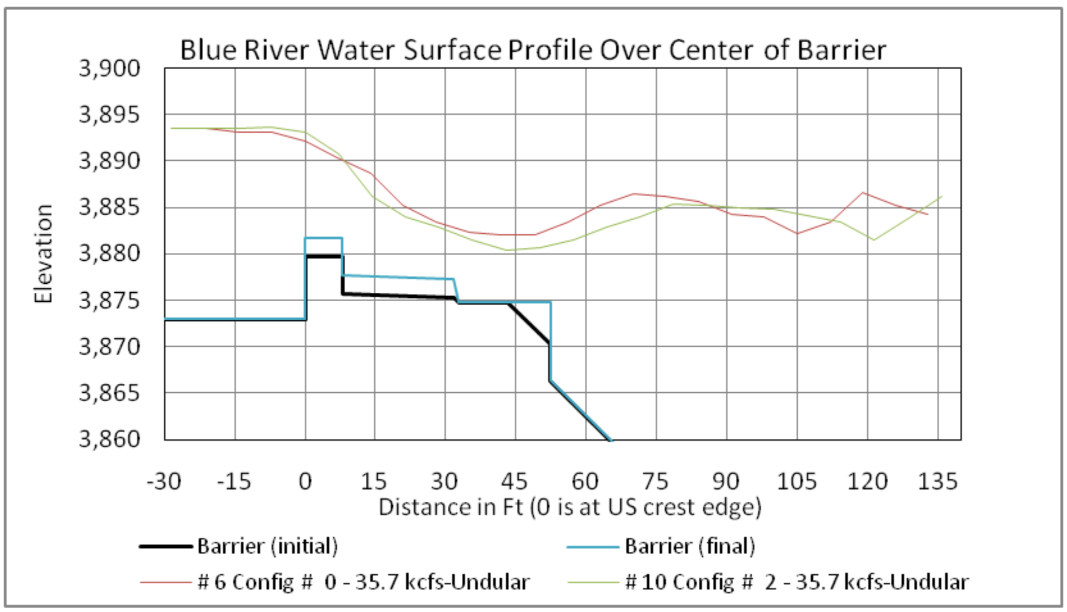

Figure 15. Undular water surface profiles for different length deflection blocks. The longer deflection block with a more abrupt termination produces a flatter, longer wave, and the undular flow condition is stable.

Training Wall

The longer deflection block worked well across most of the width of the barrier, but there was still a significant amount of scour downstream from the left end of the structure (see Figure 16). This localized scour is primarily caused by upstream approach flow conditions that concentrate flow to the left side and an expanding flow downstream that creates a large horizontal recirculating eddy on the river left side.

Figure 16. Looking upstream at localized scour on river left side of barrier.

Figure 17. Upstream approach conditions cause flow to pass over the barrier at an angle, concentrating downstream on the river left side.

Figure 18. Downstream from the barrier, a large horizontal recirculating eddy forms on the river left side.

The flow coming over the barrier moves downstream in an undular wave as discussed earlier. The downstream recirculating current flows underneath the surface wave creating a vortex along the face of the scour wall. This vortex is very efficient at scouring the scour wall and the streambed in this location.

A range of modifications, from a ramp on the deflection block to a training wall at different locations and lengths were tested in the model to reduce this scour. The most effective modification was a training wall that cut off the downstream recirculating flow. It also kept the flow from expanding immediately after passing over the barrier crest. Given the flow conditions created by the abruptly expanding canyon walls and the alluvial river bed material, this area has a high potential for scour to occur. The recommended training wall moves the scour downstream away from the structure and into a zone where the energy of the flow is not so highly concentrated. Scour continues to occur, but it is more manageable and poses less threat to the structure.

The training wall also appears to be beneficial from the viewpoint of fish barrier function. Prior to the addition of the training wall, the recirculation downstream from the barrier appeared to offer a narrow avenue at the left end of the structure where fish could easily ride with the eddy up to a point just downstream from the crest and then burst through a very narrow region of higher velocity flow to pass over the crest. The training wall extends the high velocity flow zone, which should reduce the possibility for upstream fish passage.

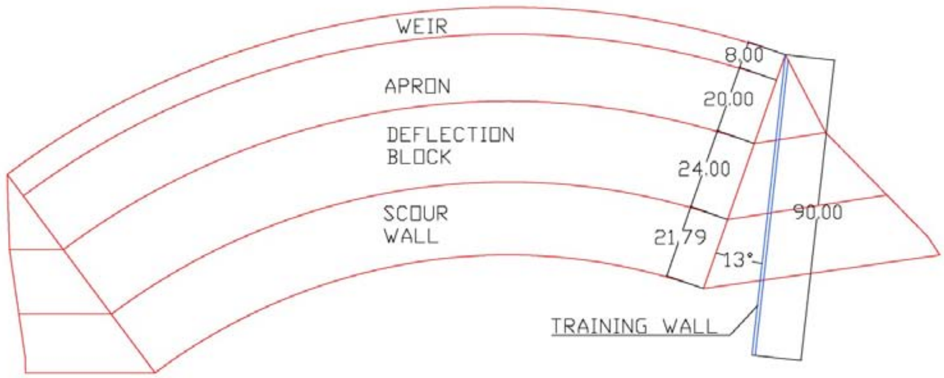

Figure 19. Plan view of the fish barrier showing location and dimensions of the recommended training wall.

The training wall needs to be tall enough to contain the flow of water coming over the barrier and cut off the downstream recirculating current for the 100-yr event. Figure 20 shows the size of the wall that was modeled and the 100-yr water surface profile. The model did show a significant amount of scour along the wall. These parameters should be taken into account in the final design of the training wall.

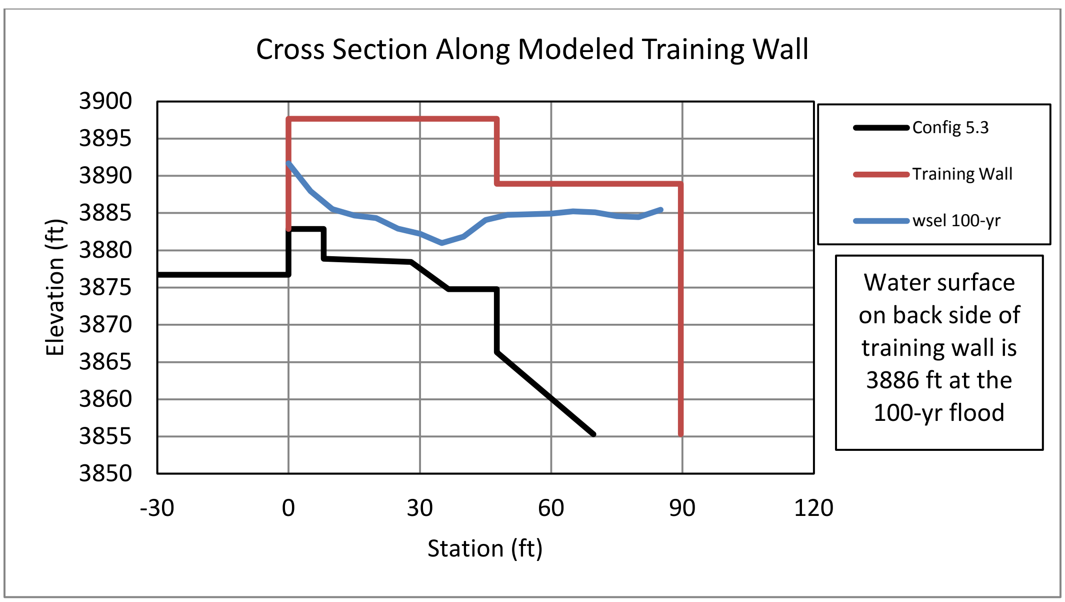

Figure 20. Elevation plot showing the modeled training wall and the 100-yr water surface profile.

Figure 21. The training wall at the 100-yr discharge.

FINAL RESULTS

Recommended Design Photos and Scour Mapping

Figures 22-31 show the recommended design, the 25-yr and 100-yr flow conditions, and the resulting downstream river channel contour maps obtained by photogrammetry. Areas of scour and deposition are highlighted in figures 27 and 31.

Figure 22. Recommended design with downstream material manually removed to make the scour wall visible for photographs.

Figure 23. Recommended design with the existing downstream topography in place.

Figure 24. Recommended design at the 25-yr discharge.

Figure 25. Recommended design showing scour after the 25-yr discharge.

Figure 26. Recommended design, 25-yr discharge, 2-ft contour map.

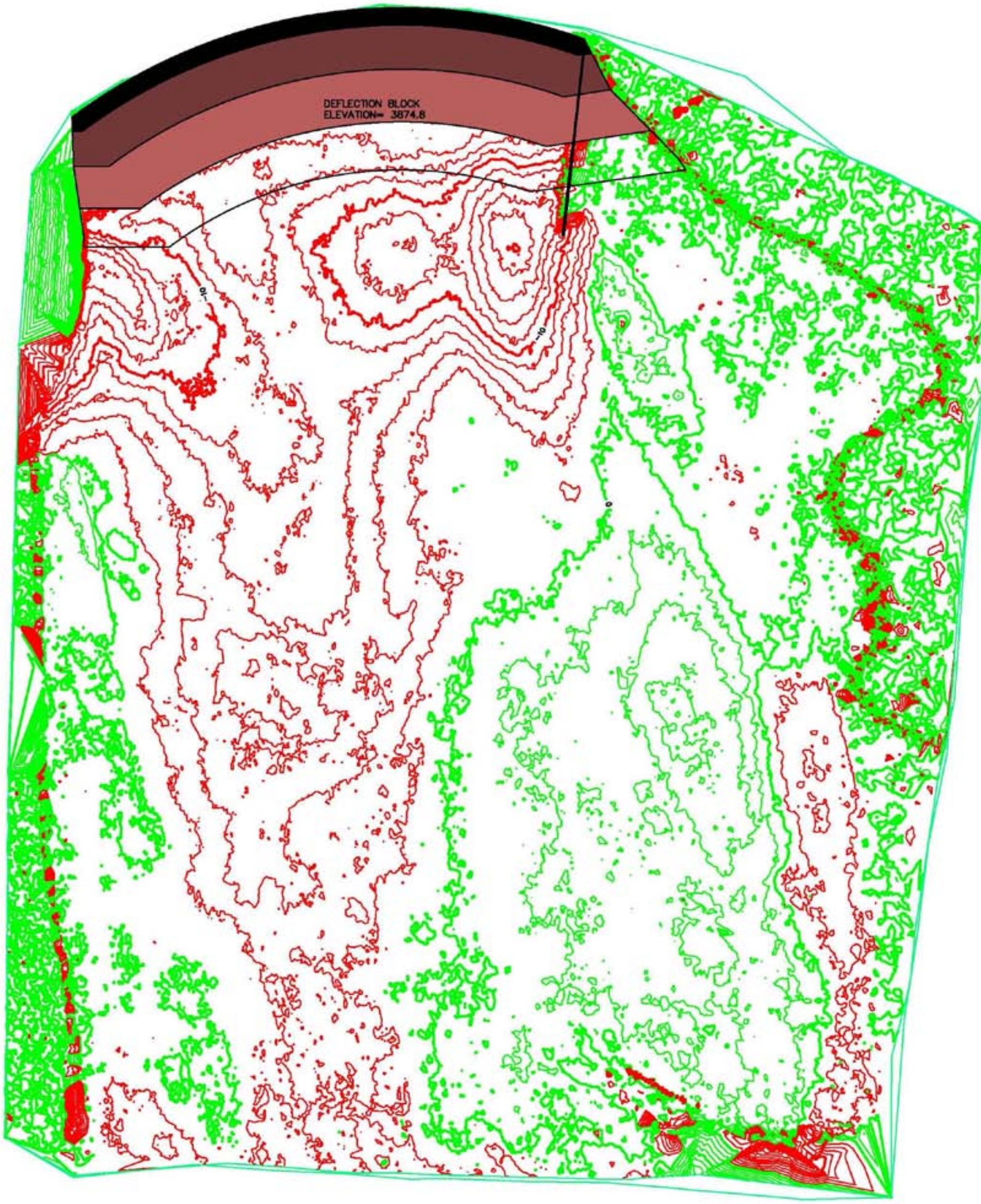

Figure 27. Recommended design, 25-yr discharge, 2-ft contour map. Red contours represent scour and green contours represent deposition.

Figure 28. The recommended design at the 100-yr discharge.

Figure 29. Scour observed with the recommended design after the 100-yr discharge.

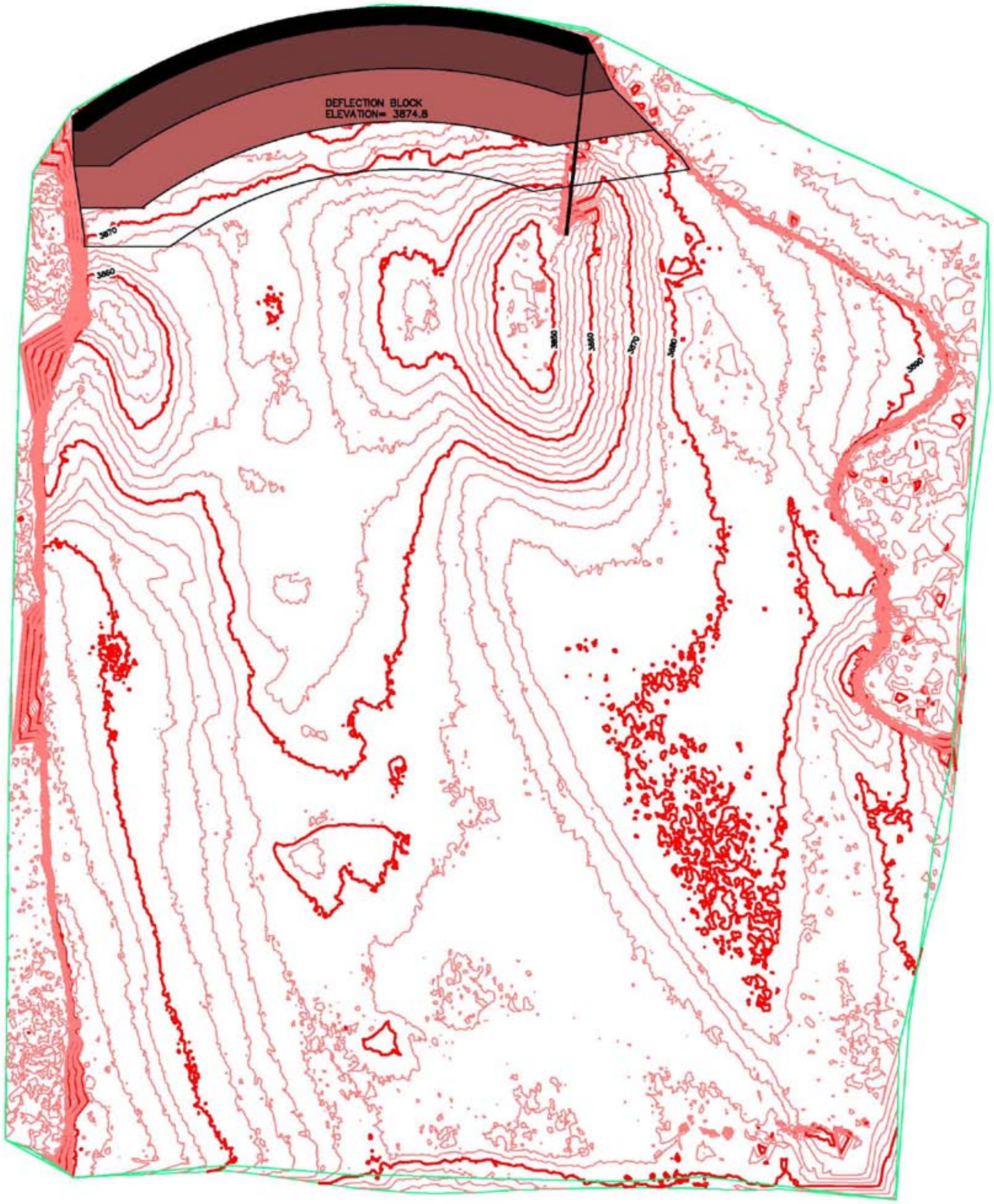

Figure 30. Recommended design, 100-yr discharge, 2-ft contour map.

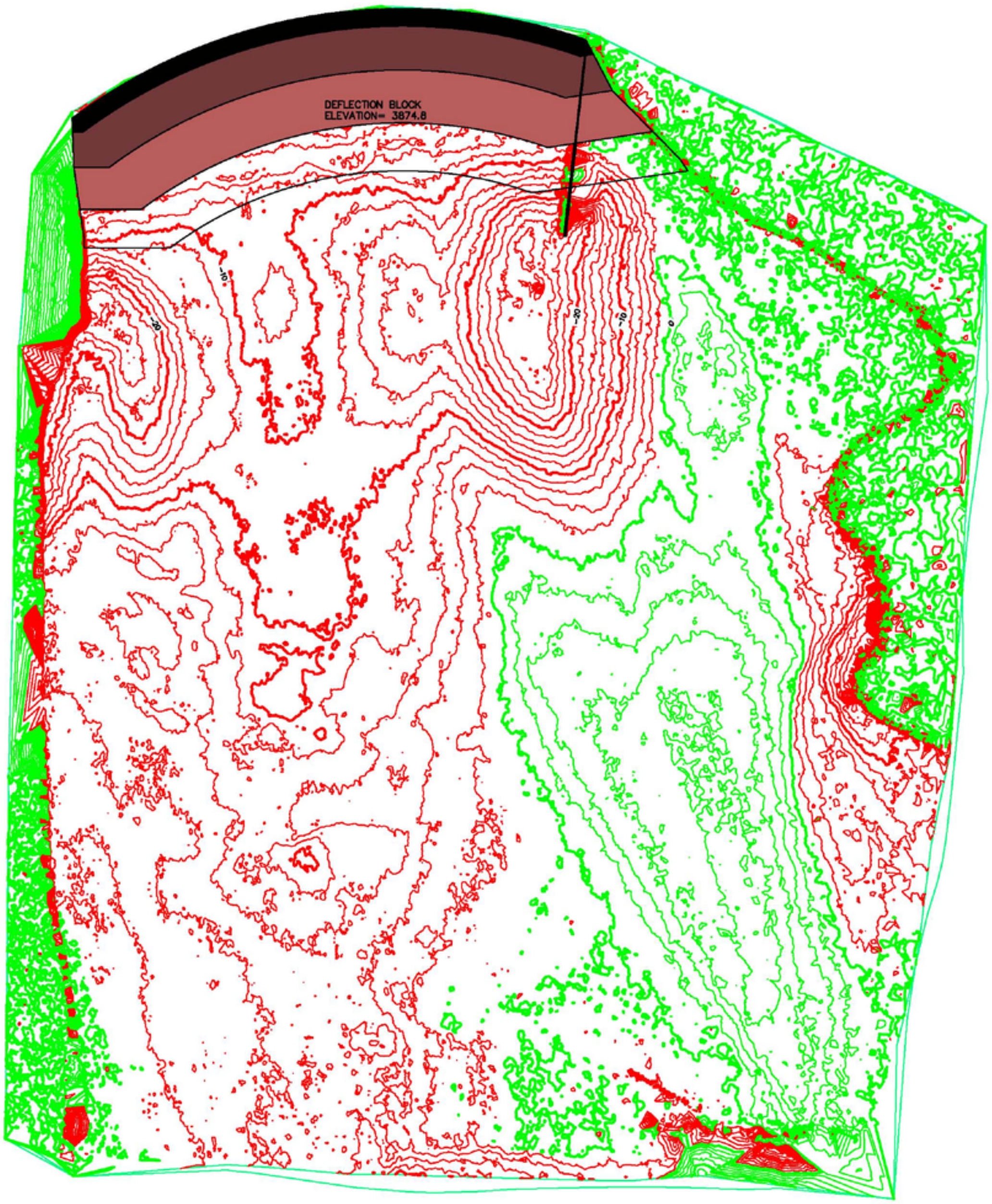

Figure 31. Recommended design, 100-yr discharge, 2-ft contour map. Red contours represent scour and green contours represent deposition.

Conclusions

- By lengthening the deflection block as shown in Figure 14 a stable, undular wave is created that produces less scour on the downstream face of the structure.
- Three-dimensional flow conditions (skewed approach flow, concentration of flow on downstream left side of structure, recirculating eddy in downstream left tailwater zone) lead to concentrated scour around the downstream toe of the left end of the fish barrier. A training wall is required on the left side to reduce this scour and move it away from the structure. It is recommended that the barrier should not have a low-flow notch, thus enabling the barrier to be lowered by the depth of the notch, 2 ft. The recommended design was modeled with the notch filled in, but the model crest was not lowered by 2 ft.
- Average depth of scour for clear water tests at the 25-yr discharge is about 10 ft with localized holes reaching 18 ft.
- The scoured ground surface above the toe of the structure after the 25-yr discharge ranged in elevation from 3862 to 3872 with an average of 3868 ft (7 to 17 ft above the toe).
- Average depth of scour for clear water tests at the 100-yr discharge is about 16 ft with localized holes reaching 26 ft.
- The scoured ground surface above the toe of the structure after the 100-yr discharge ranged in elevation from 3858 to 3870 with an average of 3868 ft (3 to 15 ft above the toe).
- The model tests provided a good relative indication of the scour associated with different design alternatives, but scour erosion in the prototype is expected to be less severe than in the model due to several conservative simplifications in the model design and operation (clear water testing, model sediment gradations that did not include all of the coarsest material fraction, etc.).

REFERENCES

Russell, K., 2010. Blue River Fish Barrier: 1-D Numerical Sediment Transport Modeling SRH-2010-11. U.S. Department of the Interior, Bureau of Reclamation, Sedimentation and River Hydraulics Group, Denver, CO.

“Hydrology and Hydraulics Blue River Fish Barriers, Arizona”, Bureau of Reclamation, Phoenix Area Office, February 2002

APPENDIX A

Table A- 1. Summary of model tests.

Test #	Date	Config	Prototype	Model
			Q Total	**Q Total**
			(cfs)	**(cfs)**
0	12/1/2009	0	35661	8.59604
1	12/8/2009	0	2609	0.628896
2	12/10/2009	0	19731	4.756133
3	12/15/2009	0	330	0.079546
4	12/15/2009	0	35661	8.59604
5	12/17/2009	0	35661	8.59604
6	12/17/2009	0	35661	8.59604
7	12/17/2009	0	19731	4.756133
8	12/21/2009	1	19731	4.756133
9	12/21/2009	1	35661	8.59604
10	1/11/2010	2	35661	8.59604
11	1/11/2010	2	19731	4.756133
12	1/13/2010	3	35661	8.59604
13	1/13/2010	3	35661	8.59604
14	1/13/2010	3	35661	8.59604
15	1/13/2010	3	35661	8.59604
16	1/13/2010	3	35661	8.59604
17	1/20/2010	4	35661	8.59604
18	1/20/2010	4.1	35661	8.59604
19	1/21/2010	4.2	35661	8.59604
20	1/22/2010	4.8	35661	8.59604
21	1/22/2010	4.9	35661	8.59604
22	1/26/2010	5	35661	8.59604
23	1/26/2010	5.1	35661	8.59604
24	1/26/2010	5.2	35661	8.59604
25	1/26/2010	5.3	35661	8.59604
26	1/28/2010	5.4	35661	8.59604
27	2/5/2010	5.3	300	0.072315
28	2/8/2010	5.3	2609	0.628896
29	2/8/2010	5.3	19731	4.756133
30	2/9/2010	5.3	35661	8.59604
31	2/16/2010	6	2609	0.628896
32	2/17/2010	6	19731	4.756133
33	2/18/2010	6	35661	8.59604

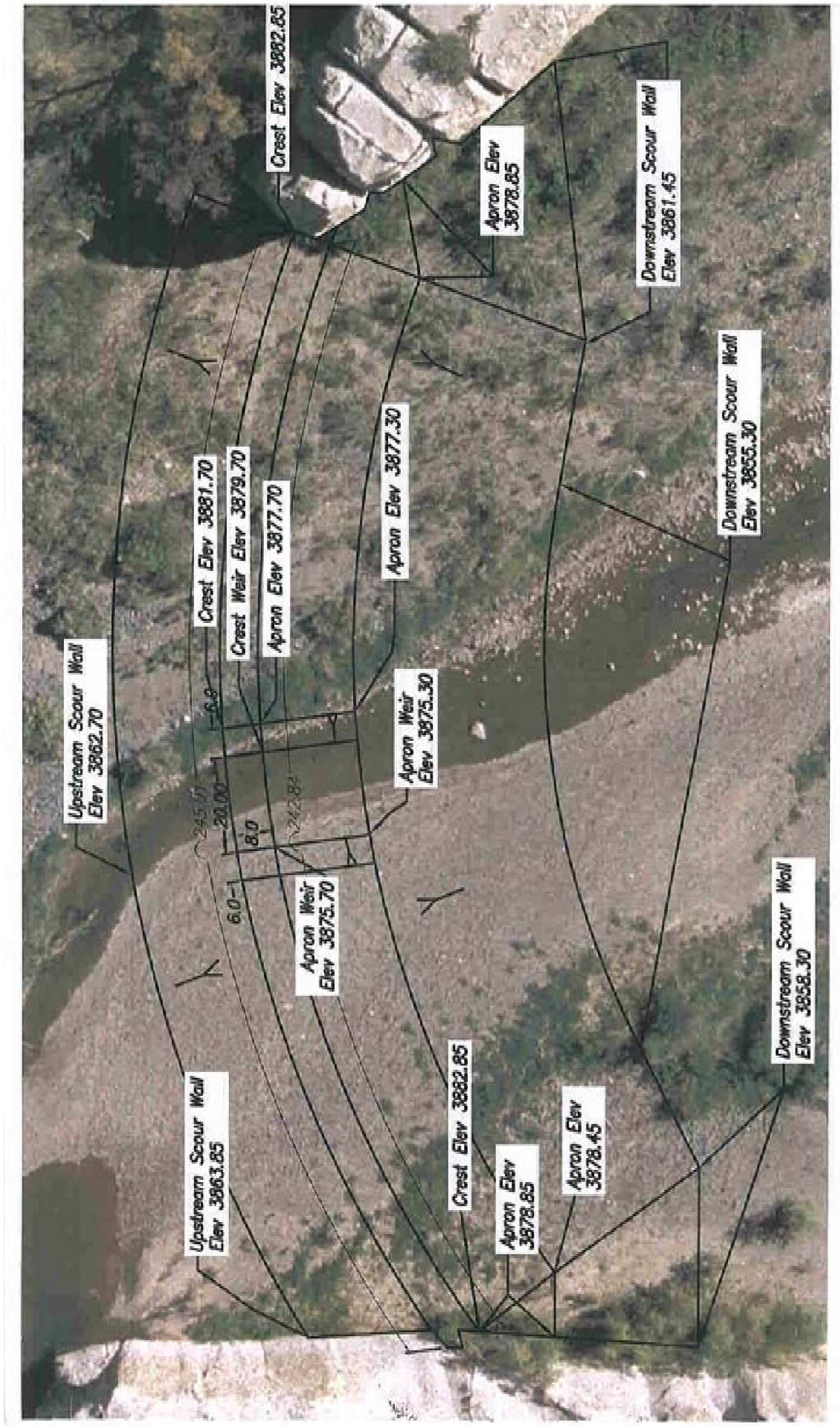

Figure A-1. Plan view of the initial design of the fish barrier structure, with elevations of key points.