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Hydraulic Laboratory Report HL-2022-03

Physical Hydraulic Modeling of the Freeman Diversion Hardened Ramp Fish Passage Alternative

Freeman Diversion
United Water Conservation District, Ventura County, California

U.S. Department of the Interior October 2022

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14. ABSTRACT

Physical hydraulic modeling of a hardened ramp fish passage alternative for Freeman Diversion (Santa Clara River, Ventura County, California) was conducted at the Bureau of Reclamation's Hydraulics Laboratory in Denver, Colorado. Two physical sediment transport models were constructed and tested at a 1:24 and 1:12 model scale to study performance of the diversion and the fish passage structures. The physical models provided results and observations over a discharge range of 100 to 6,000 ft^3/s at a 1:12 scale and 1,500 to 30,000 ft^3/s at a 1:24 scale. Testing of initial designs showed that river flow moved a large bedform into the area directly upstream of the hardened ramp and canal intake, and large volumes of sediment moved into the canal intake both with and without flushing channel operation. Operation of a flushing channel with a training wall was necessary to remove sediment deposited at the apron, canal intake sill, and canal intake gates. Flow conditions entering the hardened ramp were improved by moving the river thalweg to the left, adjacent to the riverbank. Extending the right wall of the hardened ramp further upstream with a fully rounded bullnose geometry also reduced flow separation and improved hydraulic conditions for fish exiting the ramp, especially for river flows above 1,500 ft^3/s. Flow streamlines downstream from the hardened ramp dispersed uniformly and sediment bedforms that developed downstream from the hardened ramp did not produce extreme localized scour or deposition features that would be detrimental to attracting fish into the ramp. Modifications to the configuration of rock size and placement in the low flow portion of the hardened ramp provided effective depths and velocities for upstream fish passage for a flow range of 100 ft^3/s to over 500 ft^3/s. For the discharge range of about 500 to 6,000 ft^3/s, the high flow baffled portion of the ramp provided a diversity of depths and velocities within the specified criteria range for effective fish passage. A desander concept was developed to remove sediment within the canal intake and reduce the frequency of flushing channel operations.

15. SUBJECT TERMS

hardened ramp, fish passage, steelhead, sediment management, desander

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Freeman Diversion
United Water Conservation District, Ventura County, California

prepared by

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Denver, Colorado **October 2022**

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Hydraulic Laboratory Reports

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Disclaimer

Cover Photo: 1:24 and 1:12 scale physical models of Freeman Diversion hardened ramp fish passage alternative.

Contents

Appendices

Tables

Figures

Executive Summary

Physical hydraulic modeling of the Freeman Diversion hardened ramp fish passage alternative was conducted at the Bureau of Reclamation Hydraulics Laboratory in Denver, Colorado. The Freeman Diversion is located on the Santa Clara River in Ventura County, California. Sediment transport models were constructed and tested at a 1:24 model scale and a 1:12 model scale. Two physical model scales were needed to study flow interaction among the diversion and fish passage structures within the system (1:24 scale) and to study detailed hydraulic conditions at fish passage features on and adjacent to the hardened ramp (1:12 scale). The physical models were used to provide results and observations over a discharge range of 100 to 6,000 ft^3/s at a 1:12 scale and 1,500 to 30,000 ft^3/s at a 1:24 scale. Reclamation's role and purpose in this study was to provide modeling data to assist with decision-making on design features and improvements in support of fish passage and sediment management goals.

Key findings from both physical models are summarized below.

- Baseline testing of the initial designs showed that river flow moved a significant bedform into the area directly upstream of the hardened ramp and canal intake. This bedform primarily consisted of sands and gravels. After the bedform reached a quasi-steady state, sediment continued to be transported down the hardened ramp as well as ingested into the canal intake. Several configurations with and without a flushing channel were tested and produced similar results with the large bedform present and large volumes of sediment ingested into the canal intake. A flushing channel with a training wall was necessary to remove sediment deposited at the apron, canal intake sill, and canal intake gates. Intake configurations without a flushing channel were unable to clear away the sediment deposited on these features.

- Flow conditions at the upstream end of the hardened ramp where fish exit the ramp into the upstream river were greatly improved by moving the river thalweg to the left, adjacent to the riverbank. This provided a more uniform flow approaching the hardened ramp. Extending the right wall of the hardened ramp further upstream with a fully rounded bullnose geometry also reduced flow separation and improved hydraulic conditions for fish exiting the ramp, especially for river discharges greater than 1,500 ft^3/s.

- Flow streamlines downstream from the hardened ramp generally paralleled the topography of the left bank as flow exited the ramp and dispersed uniformly as it moved downstream. Sediment bedforms that developed downstream did not produce extreme localized scour or deposition features that would be detrimental to attracting fish into the ramp. Temporary deposition in this area due to flushing or sluicing was eventually moved and reformed by continual flow exiting the hardened ramp.

- Modifications to the configuration of rock size and placement in the low flow portion of the hardened ramp provided effective depths and velocities for upstream fish passage for a flow range of 100 ft^3/s to over 500 ft^3/s. As flow increased above 300 ft^3/s, the baffles began to interact with the flow and provide an effective transition of passageways from the low flow channel into the high flow baffled area. For the discharge range of about 500 to 6,000 ft^3/s, the high flow baffled portion of the ramp provided a diversity of depths and velocities within the specified criteria range for effective fish passage (assumed to be depths greater than 1 ft and velocities less than 8 ft/s).

- Several versions of the flushing channel design were tested during the design development phase. The last version included a "castle" training wall with slots along the top and the apron floor sloping from elevation 154 ft to elevation 146.5 ft at the inlet to the flushing channel (5.2% slope). Results showed that this flushing configuration was effective at removing sediment bed loads from the canal intake and extended for some distance upstream. Additionally, lowering the invert elevation of the flushing channel gate created a larger volume to store sediment on the apron before being ingested into the diversion intake. During flushing, turbulence caused by flow passing through the slots on the top of the wall produced scour on the right side for the entire length of the training wall. The hardened ramp remained completely submerged for flushing at river flows greater than 3,000 ft^3/s.

- A desander system was developed to remove sediment within the canal intake before it reached the fish screen bays. Three versions of this system were tested in the 1:24 scale model. The latest version (Version 3) showed effective sluicing of sediment back to the river downstream of the hardened ramp. In addition, visual observations indicated that flows through the desander and sluicing culvert were well streamlined with limited shear zones and recirculation and should provide favorable hydraulic conditions for entrained juvenile fish transferred downstream. Without modulating the flow (increasing flow controlled by intake gates), effective sluicing of sediments within the sluicing culvert and downstream channel is limited to tailwater elevations lower than about 145 ft. For tailwater elevations between approximately 145 ft and 147 ft the desander system can still be effectively used if both the sluicing flow rate and sluicing time are increased to help keep the sluice culvert and channel clear of deposited sediments. Clear water (not laden with additional sediments) was needed for this to be effective and was able to be achieved by performing flushing channel operations prior to sluicing with the desander.

These findings reflect improvements and design changes that were tested in the physical models throughout the design development process. Results showed that the addition of the desander system and changes to the flushing channel and training wall enhanced the ability to manage the significant sediment load deposited at and within the canal intake. The realignment of the upstream thalweg improved flow patterns approaching the hardened ramp and provided sufficient flow depth to meet diversion demands. Also, modifications to the placement and size of rocks in the low flow channel in conjunction with the manufactured baffles provided flow depths and velocities within the specified criteria range for the hardened ramp for discharges up to 6,000 ft^3/s.

Introduction

United Water Conservation District (United Water) owns and operates the Freeman Diversion on the Santa Clara River in Ventura County, California (Figure 1). Freeman Diversion diverts water from the Santa Clara River to spreading basins for groundwater recharge at an average rate of 60,000 acre-ft per year. Freeman is a 28-ft-high, 1,200-ft-long roller compacted concrete gravity structure with a Denil fish ladder and diversion facilities. United Water currently diverts up to 375 ft^3/s but plans to file a water right change petition to divert up to 750 ft^3/s from the Santa Clara River.

Figure 1. Location of Freeman Dam (circled) on the Santa Clara River in Ventura County, California.

Figure 2. Aerial imagery of Freeman Dam facilities.

United Water is evaluating alternatives to enhance fish passage for federally endangered Southern Steelhead *Oncorhynchus mykiss* at the Freeman Diversion facility. A hardened ramp fish passage design was developed by Northwest Hydraulic Consultants (NHC) with the goal of providing successful upstream fish passage for Steelhead and Pacific Lamprey *Entosphenus tridentatus* during river flows of 45 to 6,000 ft^3/s with little or no delay at Freeman Diversion. The Santa Clara River has a gravel-cobble bed with a characteristic slope of about 0.002. The river experiences high sediment loads with transport of very fine sand to medium boulders depending on the flow event. Medium sand is the bulk of the material transported during 2- to 100-year flow events (corresponding to 9,800 to 226,000 ft^3/s, respectively, AECOM 2014). Transport of clumps of Arundo and smaller floating vegetative debris has been observed at discharges above 800 ft^3/s, while larger tree-sized woody material is transported at flows above about 6,000 ft^3/s. Large-scale channel morphology is dependent on major flow events. The ability to maintain safe and effective fish passage while managing sediment and debris in and around fishway features is critical to successful fishway performance.

NHC presented a 30% design for the hardened ramp fishway in their Design Development Report (2020). The hardened ramp design included a 90-ft-wide hardened ramp with a 5% slope and an asymmetric cross section to provide fish passage at acceptable water depths and velocities over a range of flow conditions. A 30-ft-wide triangular roughened low-flow section contained approximately 1- to 2-ft-diameter rocks with larger 3-ft-diameter rocks placed every 20 ft. The 60-ft-wide baffled ramp on a 30:1 cross slope contained 5-ft-wide vee-shaped sloped steel baffle plates with a 2.5-ft slot width. Four crest gates were included to control flow into the hardened ramp. The design also contained a 15-ft-wide sediment flushing channel and a 1.5-ft-deep and 400-ft-long fixed ogee-shaped notch in the dam to the right of the hardened ramp.

The MOD-6 configuration of the hardened ramp described in the NHC Design Development report approximately 433 ft in horizontal length at a 5% slope with an upstream invert elevation of 154.5 ft and downstream invert elevation of 134.0 ft. To meet the yield needs and provide operational flexibility proposed by United Water, the MOD-6 design was further developed into a MOD-9 design. The MOD-9 design raises the ramp by 2 ft with a horizontal extension of approximately 38 ft to maintain a 5% slope and downstream invert elevation of 134.0 ft. Bed geometry and baffle arrangement are the same for both hardened ramp configurations.

United Water contacted the Bureau of Reclamation (Reclamation) Hydraulics Laboratory in Denver, Colorado to accomplish physical hydraulic modeling of the proposed hardened ramp fish passage alternative. Two movable bed physical hydraulic models were constructed at a 1:24 and 1:12 scale to support the modeling effort. The overall purpose of the physical modeling was to provide modeling data to assist with decision-making on design features and improvements in support of fish passage and sediment management goals.

Experimental Approach

Sediment transport models were constructed and tested at a 1:24 model scale and a 1:12 model scale. Two physical model scales were needed to look at flow interaction among all the structures within the system (1:24 scale) and to resolve the details of hydraulic conditions at fish passage features on the hardened ramp and intake gates at the canal diversion (1:12 scale). The physical models were used to provide results and observations over a range of 100 to 6,000 ft^3/s at the 1:12 scale and 1,500 to 30,000 ft^3/s at the 1:24 scale.

Model Design

Model scales were chosen to provide the best opportunity to measure depths and velocities at key areas in the models while fitting within the space and discharge limitations of the Hydraulics Laboratory. A minimum Reynolds number of approximately $1x10^4$ and flow depths of at least 1 inch were maintained in each model to prevent scale effects due to water viscosity (Bureau of Reclamation 1980). Froude scaling was used for both models since gravity is the dominant force driving open channel flow within the river, hardened ramp, and canal intake in the model and prototype. Froude law similitude establishes the scaling relationships shown in Table 1.

Table 1. Froude scaling ratios for the 1:24 and 1:12 physical hydraulic models.

Scale Ratio (L_r)	Discharge	Velocity and Time	Length and Depth
24	$L_r^{5/2} = 24^{5/2} = 2{,}822:1$	$L_r^{1/2} = 24^{1/2} = 4.90:1$	$L_r = 24:1$
12	$L_r^{5/2} = 12^{5/2} = 498.8:1$	$L_r^{1/2} = 12^{1/2} = 3.46:1$	$L_r = 12:1$

1:24 Scale Model

The 1:24 scale model extended approximately 1,070 ft upstream and 620 ft downstream from the dam crest and 300 ft to the right of the hardened ramp wall (Figure 3). The model included 300 ft of the dam crest, the hardened ramp, flushing channel, and the canal intake with approximately 120 ft of its downstream extents. The left bank topography was represented with a hardened layer of concrete overlayed on plywood contours between elevations 160 ft to 190 ft (upstream of the ramp) and 146 ft to 166 ft (downstream of the ramp). The rest of the model to the right represented the active river channel with mobile sediment material (Figure 4).

The dam crest, intake apron, and intake gates were constructed of polyvinyl chloride (PVC) sheeting material while the hardened ramp, flushing channel, and canal intake structures were constructed of high-density foam. Surface roughness elements on the hardened ramp consisted of geometrically scaled rocks grouted to the invert surface and the vee-shaped flow baffles were 3D printed in rows and fastened to the ramp surface. The floor of the hardened ramp was mounted on an aluminum frame with adjustable legs to allow raising or lowering the entire ramp in unison (not changing the slope) to test the MOD-6 and MOD-9 design configurations.

Figure 3. Overlay of 1:24 scale physical model box (red) on aerial photo of site showing model extents.

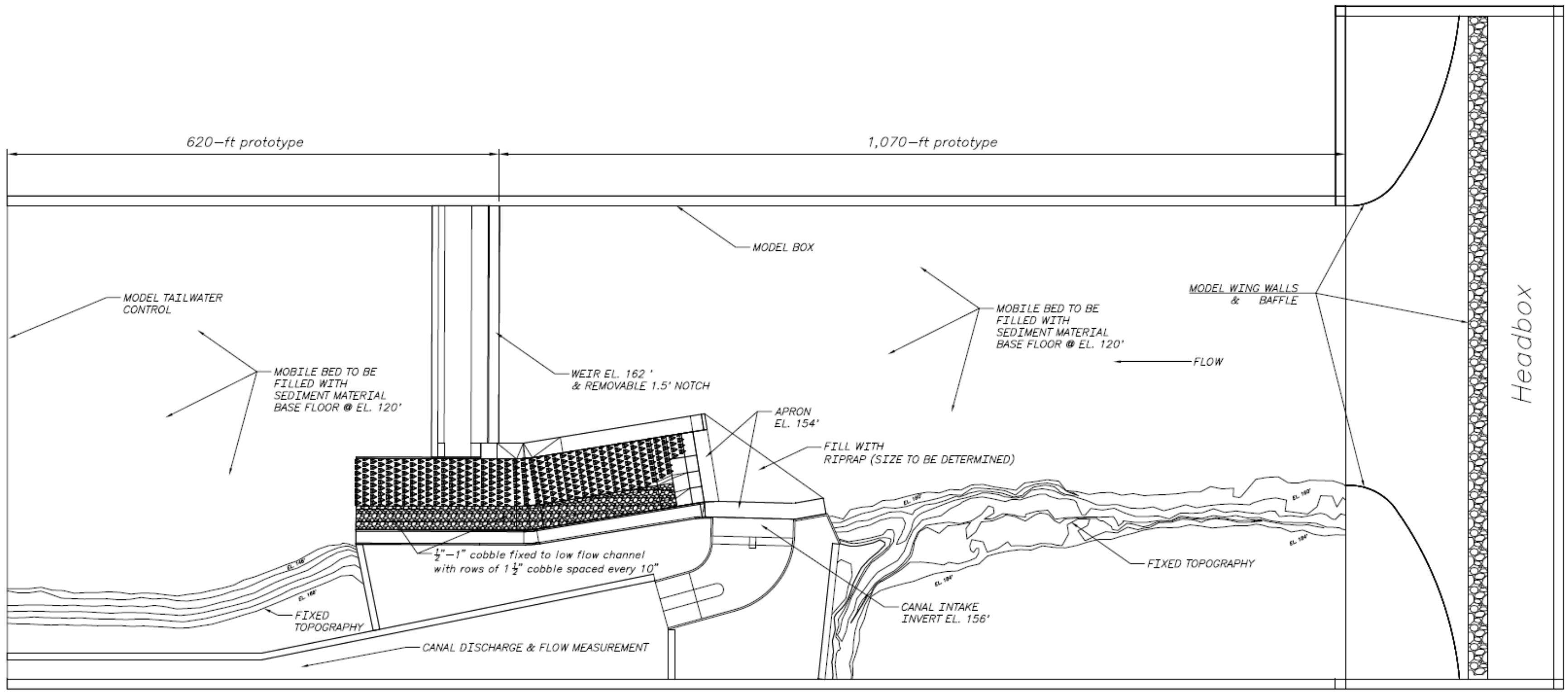


Figure 4. Plan view of 1:24 hardened ramp alternative.

The upstream boundary condition of the model was controlled by discharge coming into the model box. A large baffle wall with a “honey-comb” pattern 3-inch holes and curved entrance walls were used to distribute and condition the flow coming into the upstream extents of the model while still allowing sediment to transport with the incoming flow (Figure 5).

Tailwater elevations at the downstream boundary of the model were controlled by a series of five linear undershot gates mounted at the downstream end of the model. These gates were mounted on a threaded stem and were manually controlled.

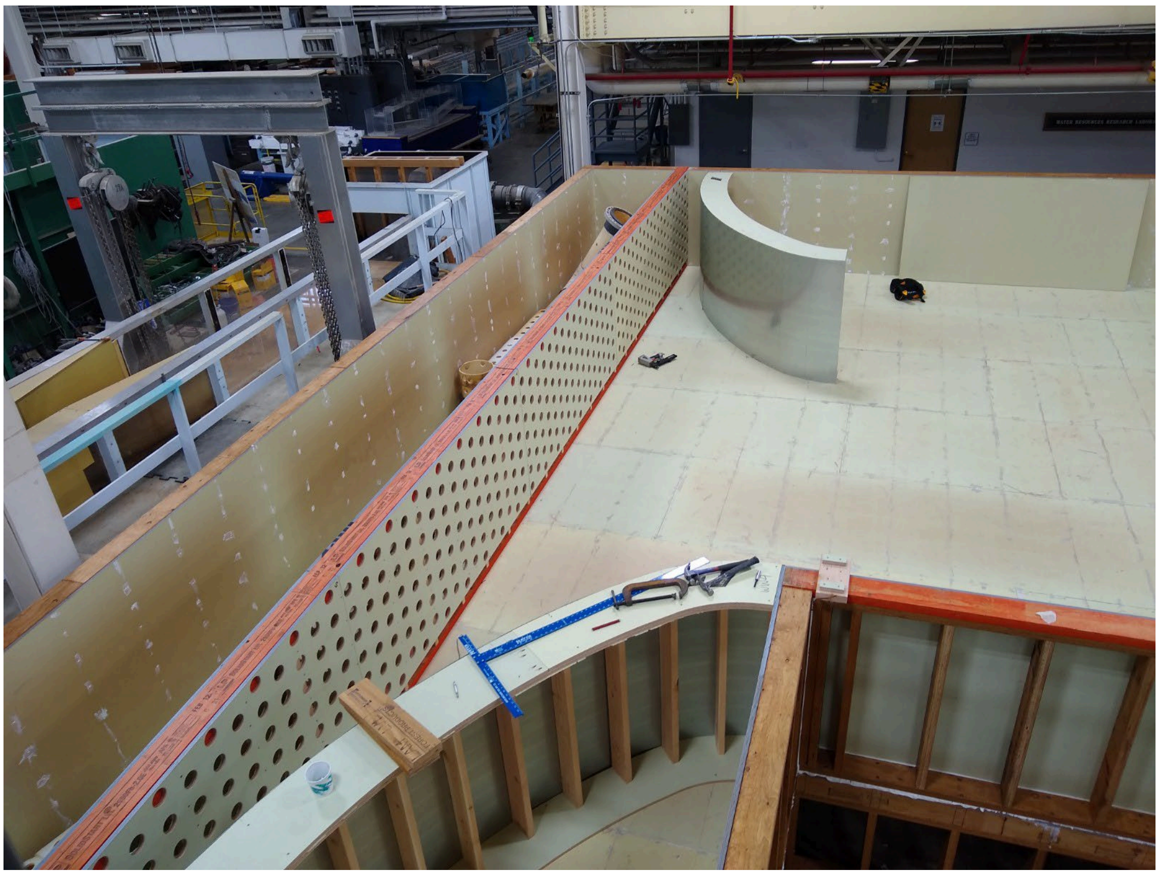


Figure 5. Baffle wall in 1:24 model with 3-inch hole ”honey-comb” pattern for flow conditioning and sediment passage as well as curved baffle walls to direct flow into the upstream extents of the model.

1:12 Scale Model

The 1:12 scale model extends about 530 ft upstream and 390 ft downstream from the dam crest and 140 ft to the right of the hardened ramp wall (Figure 6). The model included 140 ft of the dam crest, the hardened ramp, flushing channel, and the canal intake with approximately 50 ft of its downstream extents. The left bank topography was represented with a hardened layer of concrete overlayed on plywood contours for elevations from 160 ft to 170 ft upstream of the ramp and 146 ft to 150 ft downstream of the ramp. The rest of the model to the right represented the active river channel with mobile sediment material (Figure 6 and Figure 7).

The dam crest, intake apron, hardened ramp, flushing channel, and canal intake structures were constructed from high-density foam. Overshot gates for both the canal intake and hardened ramp were constructed with PVC sheet. Surface roughness elements on the hardened ramp consisted of geometrically scaled rocks grouted to the invert surface and the vee-shaped flow baffles individually fabricated on a 3D printer and fastened to the ramp surface. The floor of the hardened ramp was mounted on an aluminum frame with adjustable legs to allow raising or lowering the entire ramp in unison (not changing the slope) to test the MOD-6 and MOD-9 design configurations.

Figure 6. Overlay of 1:12 physical model box (red) on aerial photo of site showing model extents.

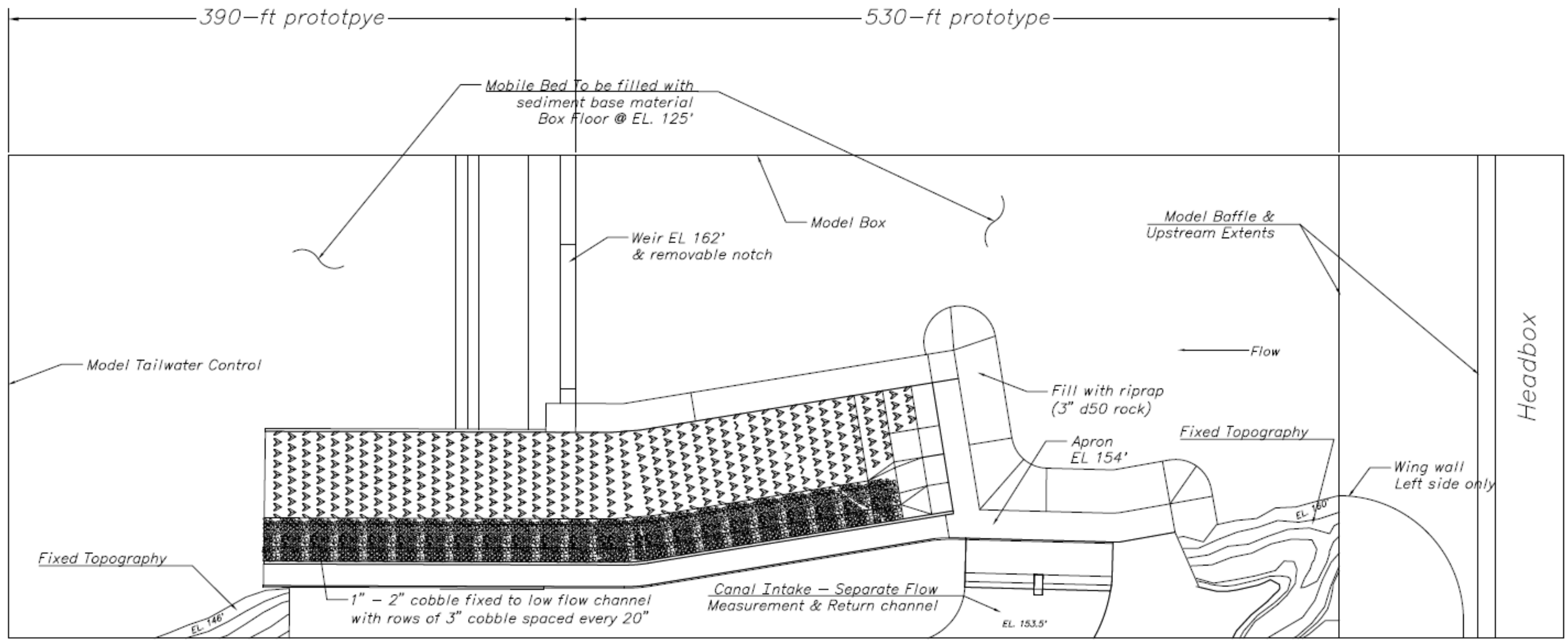


Figure 7. Plan view of 1:12 hardened ramp alternative.

Similar to the 1:24 model, the upstream boundary condition of the model was controlled by discharge coming into the model box. A baffle wall with a "honey-comb" pattern of 3-inch holes was used to distribute and condition the flow coming into the upstream extents of the model while still allowing sediment to transport with the incoming flow.

Tailwater elevations at the downstream boundary of the model were controlled by a series of four linear undershot gates mounted at the downstream end of the model. These gates were mounted in slots with linear actuators that were electronically controlled.

Sediment Scaling

The model sediment material was scaled based on prototype gradation samples collected in the Santa Clara River near the project site. Details for the model scaling design that considered appropriate mobility and settling behaviors of the scaled sediment material are described in Appendix A. To match characteristics of the prototype sediment material, a blend of three different materials was used in the physical models. These materials consisted of fine fracking sand, concrete sand, and ¾-inch rounded gravel for the 1:24 scale model and fine fracking sand, concrete sand, and 1-1/2 inch minus rounded gravel for the 1:12 scale model (gradations compared in Figure 8). The material blend ratios for each model are shown in Table 2.

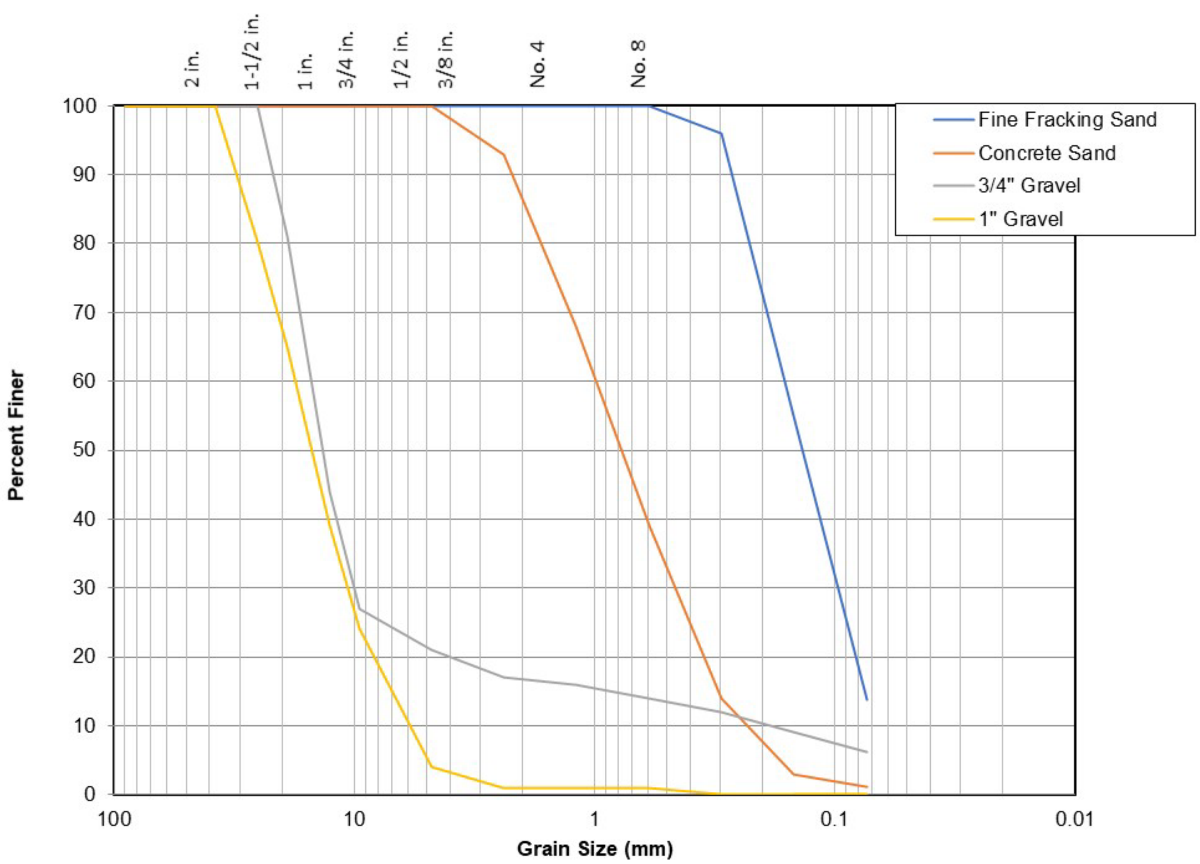


Figure 8. Gradations of model sediment used in both the 1:24 and 1:12 models.

Table 2. Ratios of materials blended by volume to create sediment mixes for the 1:24 and 1:12 models.

Material	1:24 Scale Model Percent by Volume	1:12 Scale Model Percent by Volume
Fracking Sand	20	17
Concrete Sand	28	36
¾ inch Gravel - rounded	52	0
1 inch Gravel	0	47

From the sediment design a target gradation was identified for each model scale. Common landscape or construction materials accessible to the lab were blended by volume to match the target gradation to the degree possible. Figure 9 shows the blended gradations compared to the target for each scale. Note that there is very good agreement in the range of about 20% to 50% finer at both scales which is within the range of material sizes expected to mobilize for river discharges of approximately 100 to 10,000 ft^3/s, the primary range of flow rates tested in this study.

The model sediment is believed to match the target gradations sufficiently for the models to represent qualitative patterns and trends of sediment scour and deposition at both scales. The design does not guarantee accurate quantitative results. Elevations and volumes of sediment deposits or bedforms and depths or extents of scour holes may not accurately scale geometrically to the prototype and are presented in the report only as a comparison of one configuration to another. Also, time scales for sediment development may not be the same as Froude scaling of time for hydraulics.

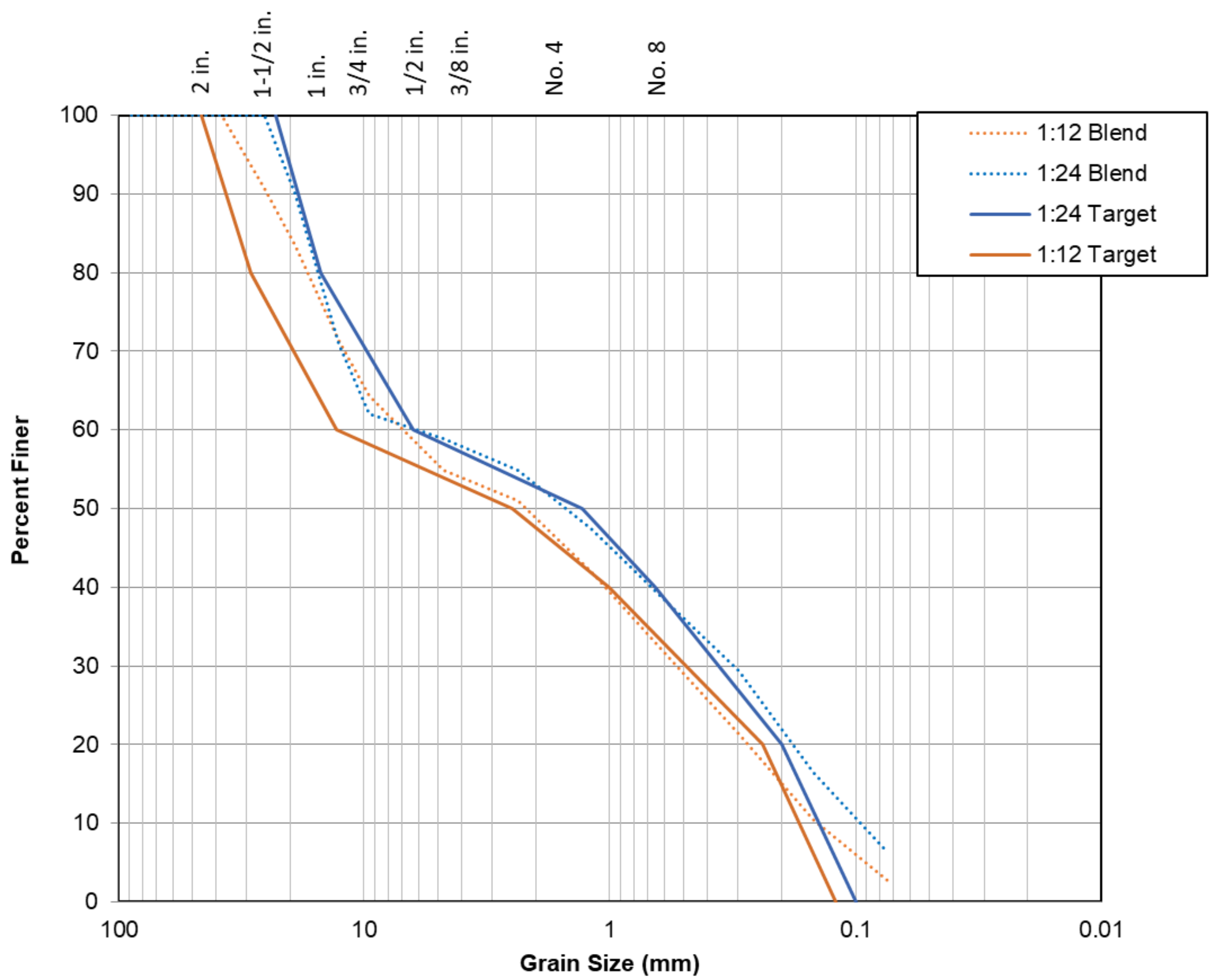


Figure 9. Sediment target and blended gradations of 1:24 and 1:12 models.

Figure 10, Figure 11, and Figure 12 show photographs of the materials used for blended sediment gradations at the lab for each model scale.

Figure 10. Photograph of materials used for the 1:24 model sediment blend.

Figure 11. Photograph of fine sand used for both sediment blends.

Figure 12. Photograph of materials used for the 1:12 model sediment blend.

Model Operation

Both models were constructed as an integrated facility with a common return channel and large pumps capable of passing larger materials and providing sediment laden flow to both model boxes. The model boxes were laid out perpendicular to each other within the allowable floor space in the lab as shown in Figure 13. The shared return channel included an overflow weir to the main lab sump for operational flexibility. The primary flow range of this study was 150 to 6,000 ft^3/s where sand and small cobble-sized materials are expected to mobilize in the river. Due to the common materials for this sand and cobble size range in the sediment design (fine and concrete sand) and similar ratios of these two materials for both model scales (Table 2), it was assumed that utilizing a common return channel and recirculation system for both models was acceptable. The common behavior of sediment patterns observed at both model scales during shakedown testing helped to justify this assumption.

The piping was arranged so that the two 8-inch horizontal pumps (recirculation pumps) with variable frequency drives operated either individually or in parallel to provide recirculated flow to both models (Figure 14). Additional pipes from the primary lab system were also included to slowly fill the model boxes in preparation for testing and for model flows either greater than the combined capacity of the sediment pumps or lower than the flow range of the flow meters on the recirculation pipes.

The 1:24 model was designed to represent river flows of 1,000 to 226,000 ft^3/s, with an oversized baffle wall to accommodate the largest flows. Flows up to 30,000 ft^3/s could be provided by the model's recirculating pump system; larger flows were achieved by supplementing with the main lab system. The primary flow range for study was 1,500 to 6,000 ft^3/s and the sediment recirculation capability was sized and adjusted primarily for this range as discussed in the Shakedown Testing section and Appendix B Baseline Summary.

The 1:12 model was designed to operate within the flow range of 150 to 12,000 ft^3/s, with the primary flow range for this study of 150 to 6,000 ft^3/s. The recirculation pump system could provide flows to the model up to 6,000 ft^3/s independently of the primary lab system. For flow rates below about 300 ft^3/s the primary lab system was used to measure these lower flow rates with the appropriately sized venturi meter for accurate flow measurement and control (

Table 3).

All testing was performed at steady-state flow conditions. Tests with unsteady flows to represent dynamic hydrographs of the Santa Clara River were not considered as part of this study. This was primarily due to the different time scales associated with water and sediment transport processes. Since sediment transport times do not necessarily scale with Froude similitude for hydraulics, it could be possible to produce sediment patterns that are not fully developed or are significantly different from reality by simulating a hydrograph. A range of steady state flows that were always tested in sequence (either rising or falling) were used instead to allow the mobile bed to fully develop and give insight into trends and patterns.

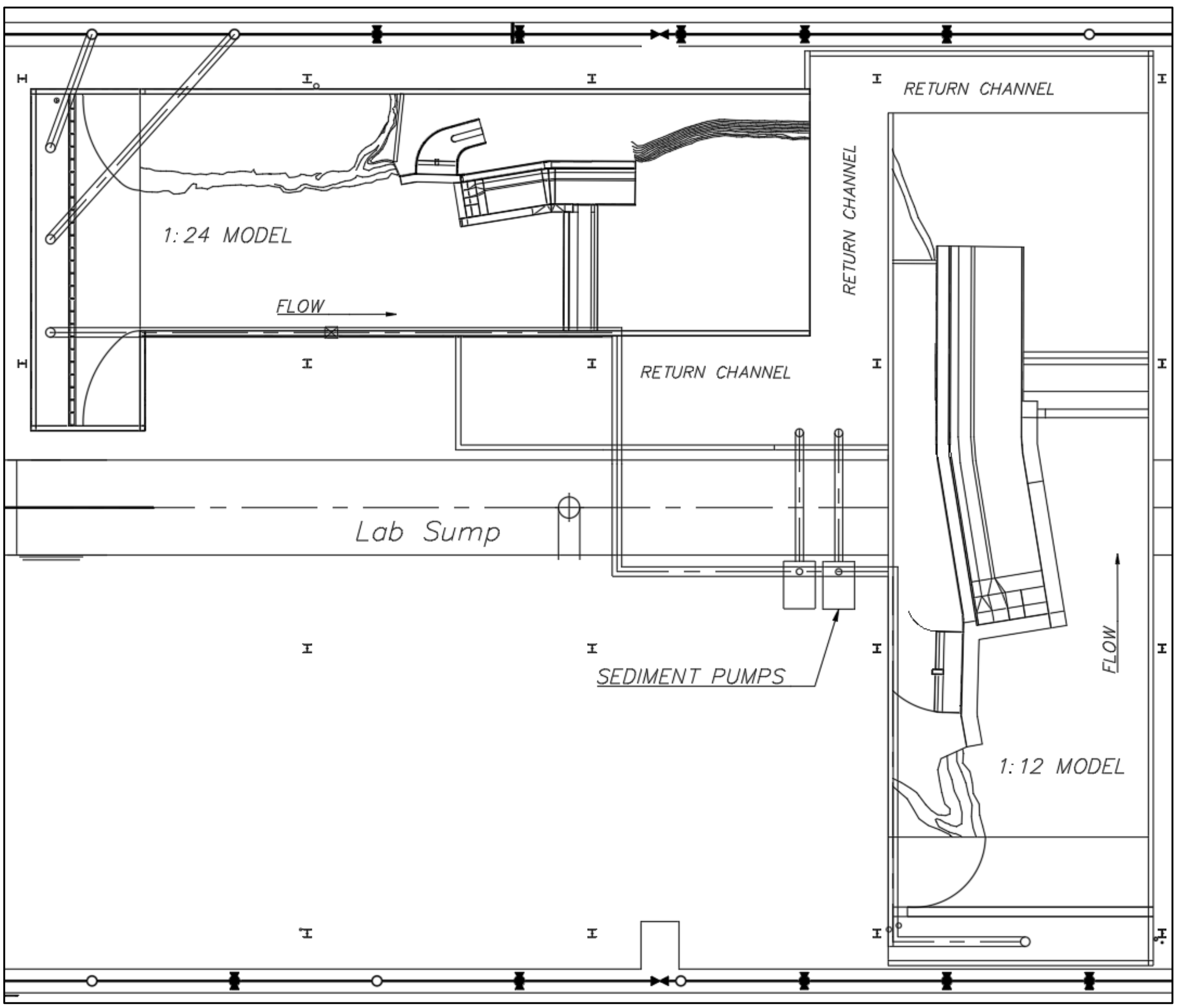


Figure 13. Layout of 1:24 and 1:12 physical models in the hydraulics laboratory with common sediment pumps and return channel.

Both models were operated by first slowly filling the model box (typically from the main lab system) to not disturb the mobile bed and then setting the desired discharge with the control valve and pump variable frequency drive once the box had filled and water reached the downstream model extent. Model boundary conditions included river discharge from the pumps on the upstream end of the model, tailwater elevations on the downstream end of the model box, and canal diversion discharge and water level controlled by canal intake gates and a downstream control gate for flow exiting the diversion. It was possible to operate both models simultaneously for flows up to 6,000 ft^3/s in the 1:24 model and 3,000 ft^3/s in the 1:12 model, however this was rarely done during actual testing.

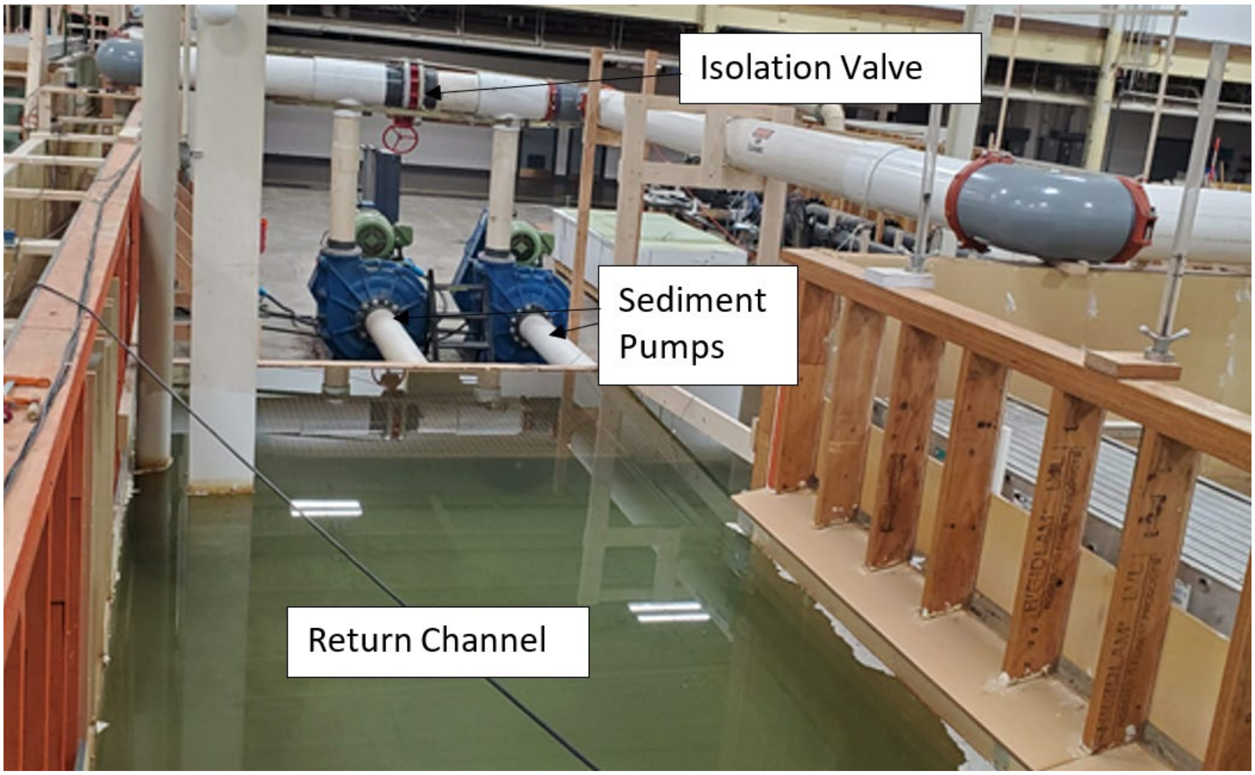


Figure 14. Photograph of common return channel and sediment pumps to recirculate sediment laden flow into both models.

Instrumentation and Data Acquisition

A variety of instrumentation was used to measure and control hydraulic conditions on both models and to record sedimentation trends and patterns (

Table 3). Both models included a data acquisition system to record and display live measurements and control settings. Systems for both models included a 12-volt power supply, analog to digital converter and laptop computer. Raw measurements were scaled, processed, recorded, and displayed live using the data acquisition software DASYLab.

Table 3. Instrumentation used for hydraulic and sediment measurements on both 1:24 and 1:12 models.

Measurement		Sensor / Measurement Technique
Discharge	River (1:24)	Siemens Electromagnetic Flowmeter
	River (1:12)	Siemens Ultrasonic Flowmeter
	River (1:12, < 300 ft^3/s)	Venturi Flow Meter
	Canal Intake Diversion	MassaSonic Downlooker (V-Notch Rating)
	Dam Crest	MassaSonic Downlooker (Rating)
Water Level	Elevation	MassaSonic Downlooker
	Depth - Point Locations	Steel Ruler
Velocity	Flow Patterns	LSPIV (Large Scale Particle Image Velocimetry) from GoPro video
	Point Measurement (depth > 2 inch)	Flow Tracker ADV
	Point Measurement (depth < 2 inch)	Nixon Meter
Sedimentation	Topography	Photogrammetry
	Topography	FARO Focus 5 Laser Scanner
	Depth - Point Locations	Steel Ruler
Intake Gate Position	Elevation (1:24)	Scale on side walls of intake
	Elevation (1:12)	Potentiometer

1:24 Data Collection

The 1:24 data acquisition system recorded water levels and discharge for each model run. Water surface elevations were measured with MassaSonic acoustic downlooking sensors at several locations shown in

Table 4 and Figure 15. Total river discharges were measured with a Siemens electromagnetic flow meter, canal discharge was measured with a V-notch weir and flows over the dam crest were estimated with water surface elevation rating curves developed during shakedown testing.

Point measurements of both flow depth and velocity were made primarily on the upstream end of the hardened ramp at locations of the four ramp crest gates. Velocities at these locations were measured with a Nixon rotary meter due to shallow depths. Large Scale Particle Image Velocimetry (LSPIV, or simply PIV) was also used for the area near the canal intake and hardened ramp exit extending upstream (see LSPIV section).

Bathymetric maps showing bed changes and extents of sediment deposition and erosion were created using photogrammetry for the baseline testing completed in late 2021. In early 2022 the Hydraulics Lab acquired a FARO Focus 5 Laser Scanner for bed mapping from that point on.

Table 4. Water level sensor locations on 1:24 model.

Water Level Sensor Number	Location	Distance from Dam (ft)	Description
1	Upstream Channel	660	Center of channel about 150 ft from right model extent
2	Upstream Intake	396	Immediately upstream of the canal intake near left wall
3	Downstream Intake	300	Center of canal intake about 60 ft downstream from intake gates
4	Dam Crest - Right	12	Near the river right model extent
5	Dam Crest - Left	12	Near the ramp wall, river left side of dam
6	Tailwater	-256	Immediately downstream of the hardened ramp entrance

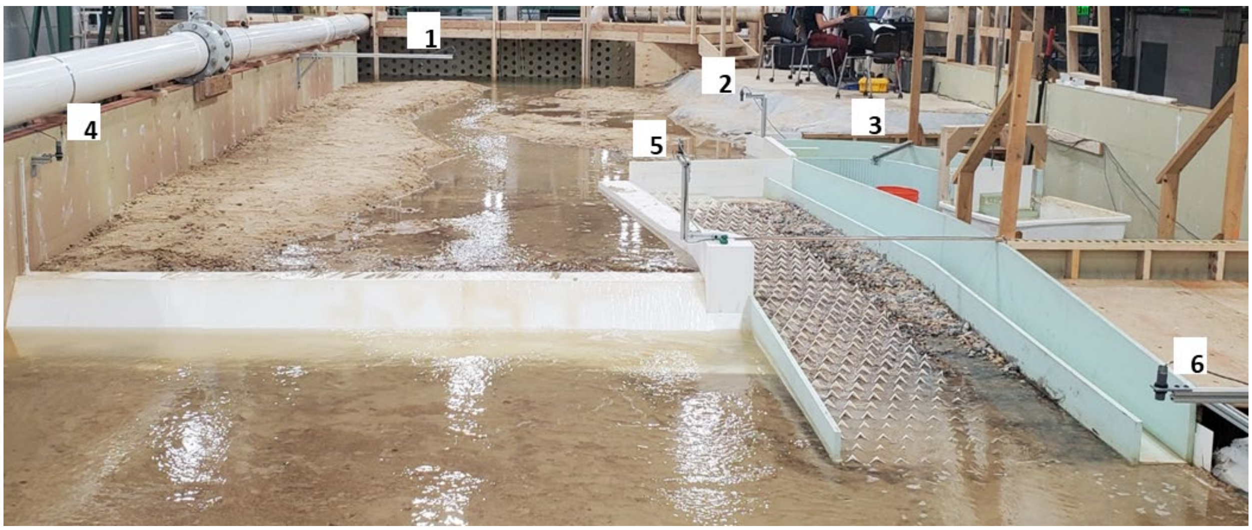


Figure 15. View of water level sensor locations on 1:24 model (looking upstream).

1:12 Data Collection

The 1:12 data acquisition system recorded water levels, canal intake gate elevations, and discharge for the canal diversion. Water surface elevations were measured with MassaSonic acoustic downlooking sensors at several locations shown in Table 5 and Figure 16. Total river discharge was measured with a Siemens acoustic flow meter but was not recorded electronically during testing. Flows shown on the meter's display screen were recorded manually. Canal discharge was measured with a V-notch weir and flows over the dam crest were estimated with water surface elevation rating curves developed during shakedown testing similar to the 1:24 model.

Point measurements of both flow depth and velocity were made primarily on the upstream end of the hardened ramp at locations of the four ramp crest gates (Figure 17). Velocities at these locations were measured with a FlowTracker Acoustic Doppler Velocimeter (ADV) for model flow depths greater than about 2 inches and a Nixon rotary meter at shallower depths. Point and velocity and depth measurements were also made on the hardened ramp structure during design development of fish passage features. PIV was also used for the area near the canal intake and hardened ramp fishway exit (upstream end of ramp) extending upstream as well as at key locations on the hardened ramp (see LSPIV section). Bathymetric maps showing bed changes and extents of sediment deposition and erosion were created using a FARO Focus 5 Laser Scanner and TecPlot software.

Table 5. Water level sensor locations on the 1:12 model.

Water Level Sensor Number	Location	Distance from Dam (ft)	Description
1	Upstream Intake	396	Immediately upstream of the canal intake near left wall
2	Downstream Intake	300	Center of canal intake about 30 ft downstream from intake gates
3	Dam Crest - Left	12	Near the ramp wall, river left side of dam
4	Tailwater	-256	Immediately downstream of the hardened ramp entrance

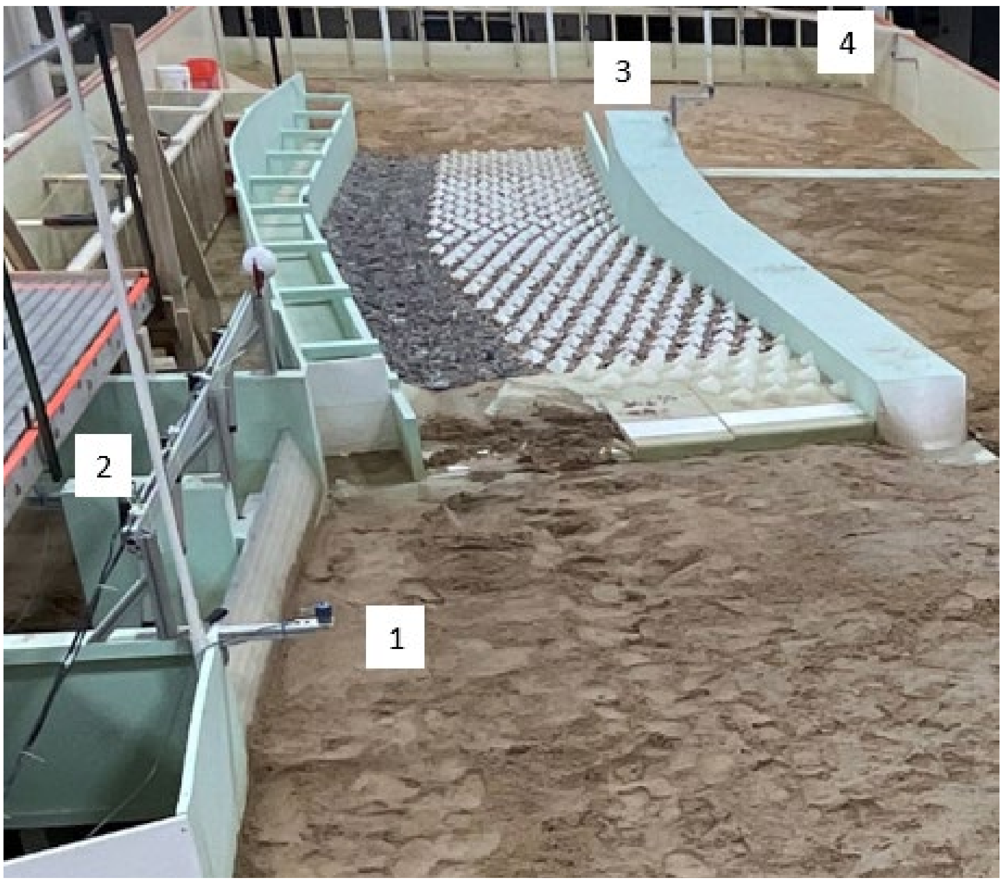


Figure 16. View of water level sensor locations on 1:12 model (looking downstream).

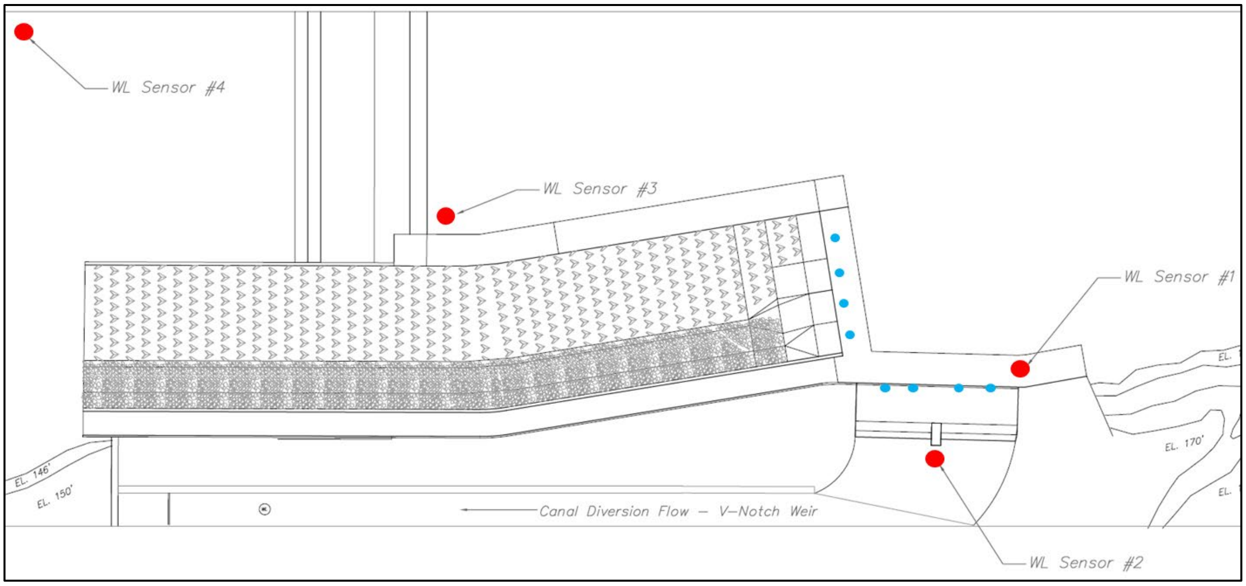


Figure 17. Layout of water level sensor locations in the 1:12 model (red) and point velocity and depth measurement locations (blue).

LSPIV

Large-scale particle image velocimetry (LSPIV) was used to capture surface velocities for areas of interest on both models. To capture these data, several GoPro Hero10 cameras recorded videos at a rate of 30 frames per second. Seeding material was evenly dispersed into the model until a minimum of 10 seconds of full coverage was obtained. Frames were separated into individual images using RIVeR 2.2. These frames were then processed using PIVLab software. PIVLab outputs velocity vector maps of the water surface, which were saved in ASCII comma separated format and brought into TecPlot360 to generate velocity color contour plots.

On both the 1:24 and 1:12 models, LSPIV was used to produce velocity plots of the upstream region of key features. This included the hardened ramp fish exit, bullnose, and canal intake. Additionally, on the 1:12 model, LSPIV was used to develop velocity fields around the low flow channel rock configurations and downstream of the hardened ramp.

Photogrammetry and LiDAR Scanning

To quantify the behavior of the movable bed material both, photogrammetry and terrestrial LiDAR scanning techniques were used. The photogrammetry technique utilized a Sony Alpha 7r 24-MP camera to obtain over two hundred overhead photographs of the upstream and downstream area. The photos were aligned and analyzed in Agisoft Metashape, a commercially available Structure from Motion (SfM) software (Agisoft, 2022). This method allowed for a point cloud to be refined to a variance of ±0.17 inches on average. The point clouds were processed in AutoCad Civil 3D to produce color contour plots of bed elevations or comparative differences.

After early 2022, point clouds of the movable bed were obtained with a FARO FocusS70 terrestrial LiDAR scanner. The 3D scans were analyzed in Scene, FARO's 3D scan processing and registration tool (FARO, 2022), which produced a point cloud with 1-3 mm model resolution. Collected point cloud data were brought into AutoCAD and TecPlot Focus where color contour maps were generated.

Shakedown Testing

"Shakedown" testing refers to initial tests of the physical models to first confirm basic operations such as flow entering and exiting the model correctly, instrumentation working properly, and flow passing through the model structures as intended. Tests then included verifying that the boundary conditions corresponded to the design and that flow conditions were an accurate representation of the prototype. Further shakedown testing was needed for sediment transport models to verify proper transport of the designed sediment materials within the model as well as to establish time durations of test runs for the sediment to reach a quasi-steady state.

1:24 Model

Flume Sediment Transport Tests

Initial shakedown testing began while the 1:24 scale physical model was still under construction. Simple tests were conducted in the Hydraulics Laboratory's 3-ft tilting flume to confirm sediment transport characteristics of the 1:24 scale designed sediment blend before large volumes of the sediment materials were acquired. A sample of the designed sediment blend was placed in the flume with a representative bed slope of 0.002. A range of velocities and corresponding "critical" material sizes expected to begin mobilization were observed in the flume (Table 6). A ruler was secured to the bottom of the test section to help identify approximate material sizes that began to be transported (Figure 18). Visual observations were recorded with video.

Table 6. Critical grain sizes that begin to be mobilized at the corresponding velocities according to Shield's diagram used for sediment design.

Prototype Velocity	***Critical Grain Size***	
ft/s	*mm*	*inch*
3.9	24	0.94
4.1	36	1.42
5.2	48	1.89
10.8	120	4.72
15.2	300	11.81

Figure 18. Photograph of ruler and 1:24 scale sediment blend used for visualization of sediment movement.

Sediment particle sizes that began to mobilize in the flume tests were plotted on Shield's diagram at their corresponding velocity (Figure 19) to be compared to the critical parameter for material transport. In other words, data points represent particles that are either beginning to move or have already started moving and fall very close to the critical Shield's parameter (yellow line). These observations helped add confidence that the designed sediment blend would transport appropriately for the expected range of river discharges and velocities. Due to these initial results and observations, this flume test was not repeated for the 1:12 sediment blend. Shield's diagram and parameter and their relevance to the sediment design of the current study are discussed in detail in Appendix A.

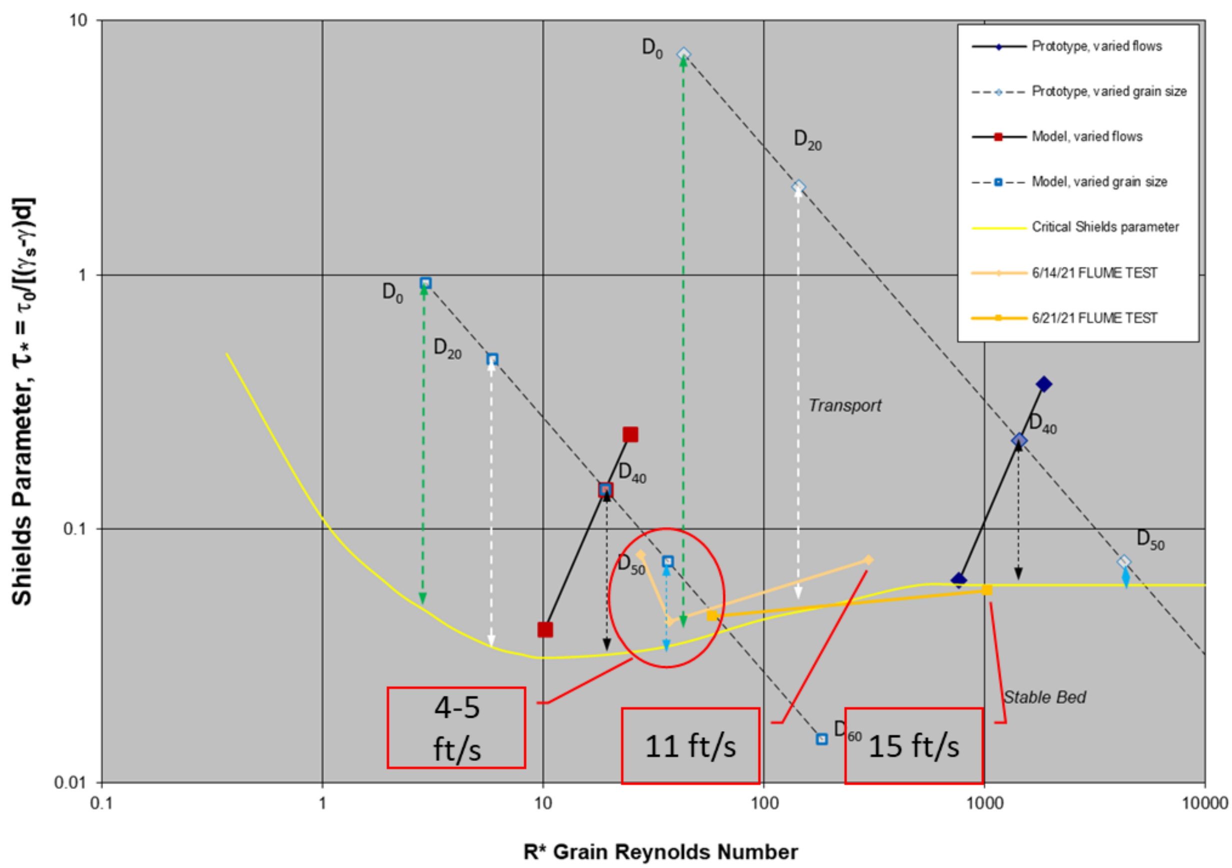


Figure 19. Critical grain sizes that began to mobilize near the critical Shield's parameter (yellow) adding confidence that the 1:24 sediment blend was designed correctly for the range of prototype velocities expected.

Adjustments to Upstream Topography and Sediment Materials

Initial test runs in the 1:24 model focused on upstream flow conditions approaching the hardened ramp and dam. Velocity profiles from NHC's two dimensional (2D) HEC-RAS models as well as video observations from previous flows over Freeman Dam were used to adjust the upstream river topography to provide flow conditions more realistic of the prototype site. Visual observations were made in the model of flow passing over the dam in a manner similar to that shown in Figure 20 where flow is skewed to the left due to the vegetation and channelization of the river.

Due to the dynamic characteristics of the river, there was much discussion between United Water's engineering team, NHC, special advisor Dr. Larry Weber, State of California Department of Fish and Wildlife, and the NOAA Fisheries about the testing approach. During shakedown tests a baseline topography (Figure 21) representative of site conditions was selected to be consistently applied for all baseline testing.

Figure 20. Aerial footage of 23,000 ft^3/s discharge over the dam crest, overlayed on a lower-flow aerial image and approximate upstream extents of the 1:24 model, outlined in red.

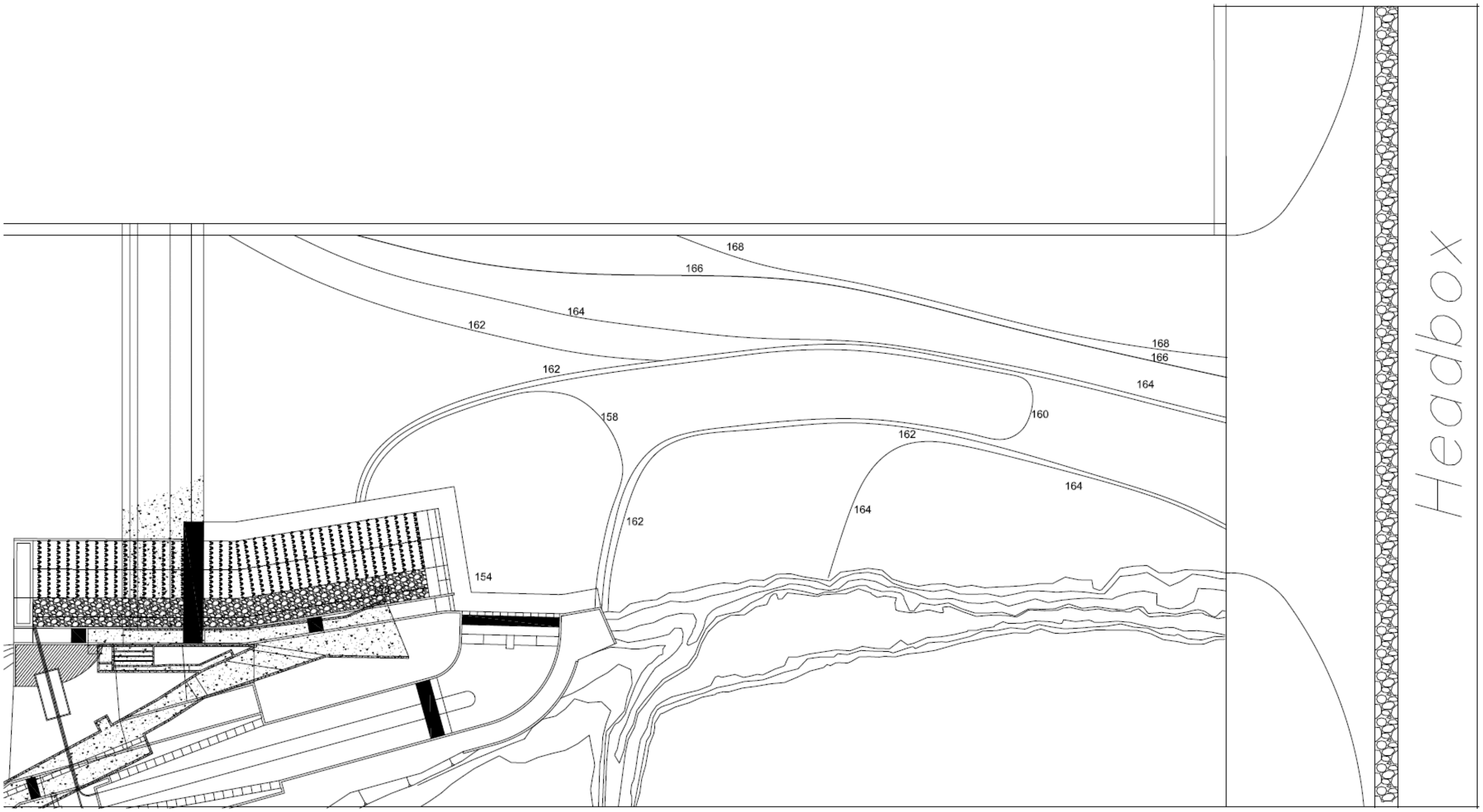


Figure 21. Layout of upstream topography adjustments used in 1:24 baseline tests.

Figure 22. Photograph of upstream topography that was manually set before testing (looking downstream).

Once the approach conditions were confirmed, the focus of shakedown testing shifted to proper sediment transport in the model. Visual observations from the field were helpful in ensuring the sedimentation was representative. Initial tests showed that the ratio of larger cobbles and boulders was too high in the model and that there were insufficient sands and cobbles present to accurately represent sediment behaviors in the river. Additional blends of fine and concrete sand were added to provide more smaller materials that tend to transport over the primary discharge range to be used for testing in this model (up to 12,000 ft^3/s). This agreed with observations of sediment transport in initial flume tests as well as with visual observations of the material size range that most commonly transports in the prototype. Figure 23 compares bed materials upstream of the hardened ramp near the beginning and end of shakedown testing to show the increase of smaller materials.

Figure 23. Photographs of the bed material comparisons near the beginning (left) and end (right) of shakedown testing where additional fine materials were added to the top layer for more realistic sediment conditions expected for a flow range of 1,000 to 12,000 ft^3/s.

During shakedown testing (with the MOD-6 design configuration), the model was evaluated to determine time durations needed to reach a quasi-steady state condition, with no further significant changes occurring with additional run time. Shakedown tests also highlighted the need for consistent sediment rates coming into the model with flow from the upstream headbox, which varied with flow rate. Sediment was "fed" into the model from a basin filled with sediment just downstream of the baffle wall and upstream of the model entrance. Occasional manual raking was needed to assist feeding sediment into the model which may account for minor differences in the quantity of sediment between test results. However, any manual intervention was performed as consistently as possible among all test runs by raking sediment from the upstream basin once the aluminum floor transition at the entrance to the river channel began to be visible.

1:12 Model

Shakedown testing of the 1:12 model followed similar steps as those taken for the 1:24 shakedown. However, since the 1:24 model was constructed and tested first, results, observations and patterns from that model were used to help verify acceptable performance of the 1:12 model within its reduced extents. Similar topography was installed in the upstream reach and produced flow patterns approaching the dam and hardened ramp that were very similar to those seen in the 1:24 testing. Water surface elevations were also compared at similar discharges, such as those shown in Table 7 for 6,000 ft^3/s.

Table 7. Water level comparisons for the 1:24 and 1:12 models at 6,000 ft^3/s during shakedown of the 1:12 model.

River Flow (ft^3/s)	Upstream Intake (ft)		Dam Crest Left (ft)	
	1:24 Model	***1:12 Model***	***1:24 Model***	***1:12 Model***
6,000	161.9	162.5	162.6	162.6

Observations of sedimentation patterns were also made and compared at both scales. Photographs in Figure 24 show similar sediment patterns following a discharge of 6,000 ft^3/s upstream of the hardened ramp and canal intake, including deposits on gates 1 and 2 of the hardened ramp as well as the canal intake gates. Point elevations of the bed at the same locations produced similar results. Scour upstream of the hardened ramp wall bullnose is another prominent feature that was repeatable at both model scales.

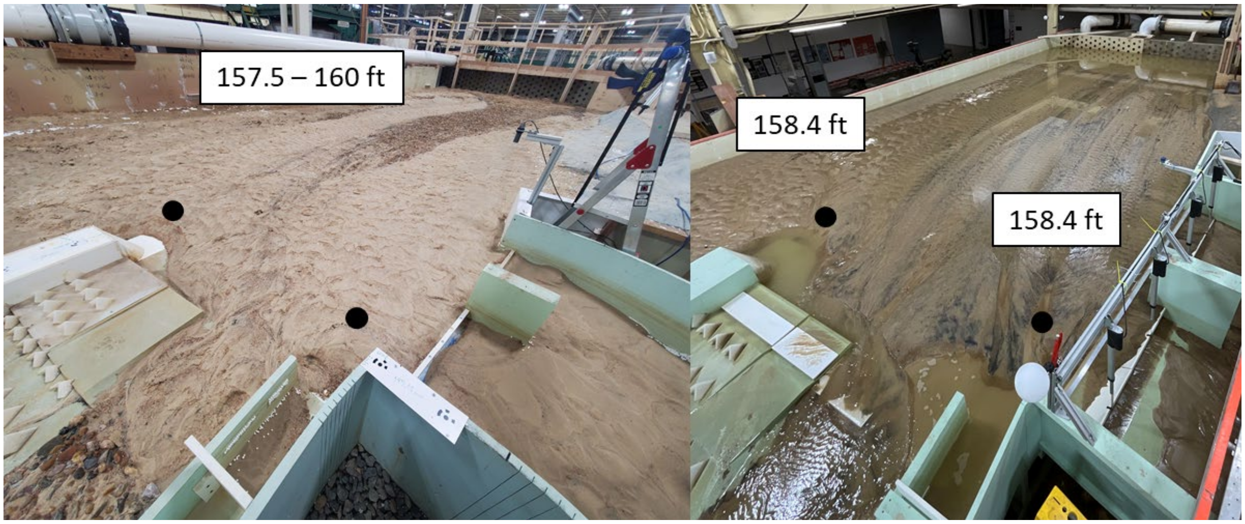


Figure 24. Photographic comparisons of sediment patterns after 6,000 ft^3/s in the 1:24 model (left) and 1:12 model (right).

Experience testing the 1:24 model during shakedown and baseline testing showed that time durations could be shortened by "pre-loading" the model with sediment loads near the canal intake and hardened ramp exit. Run time durations to reach quasi-steady state were tested in the 1:12 model during shakedown and the following run times were determined (e.g., 6,000 ft^3/s in Figure 25).

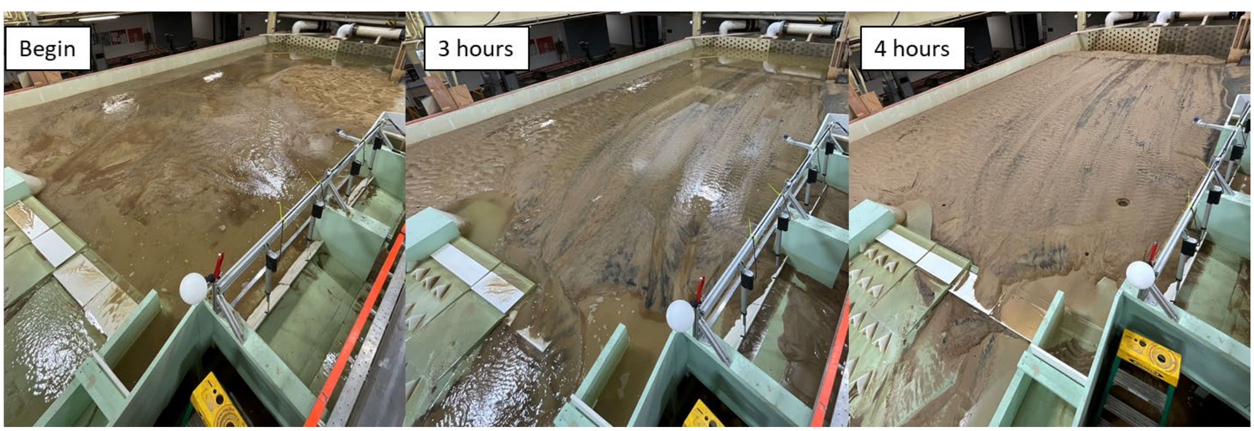


Figure 25. Timelapse photographs of the 1:12 model at 6,000 ft^3/s to determine run times required for sediment patterns to reach equilibrium.

Shakedown tests considered consistent sediment rates coming into the model with flow from the upstream headbox. In the 1:12 model, occasional manual raking was needed to assist feeding of sediment similar to the 1:24 model. However, the need for manual intervention was greatly reduced in the 1:12 model due to the design of the headbox and sediment basin just downstream of the baffle wall which generally fed sediment into the model naturally along with the flow coming into the model.

Observations of flow and sediment patterns downstream of the hardened ramp differed from those in the 1:24 model for flows of 3,000 ft^3/s and higher. This was due to the reduced downstream extent of the 1:12 model that truncated the flow exiting the model and affected its local behavior. This finding showed that the 1:24 model was the most reliable indicator for sediment and flow patterns in the river downstream of the ramp. However, local flow patterns on the downstream fish entrance of the hardened ramp itself did not appear to be affected by the downstream boundary; the boundary affected only the river further downstream.

Baseline Testing Configurations

Baseline tests were conducted in both the 1:24 and 1:12 models using initial 30% design configurations. The main intent for these initial baseline tests was to provide initial comparisons between MOD-6 and MOD-9 design alternatives. No improvements or modifications were made during baseline testing, but results were used to inform design changes made later in the design development phase of the study. Specific objectives of baseline testing included:

- Identify hydraulic and sediment differences between MOD-6 and MOD-9 design configurations
- Identify hydraulic and sediment differences between design configurations with and without a flushing channel
- Observe and document qualitative sediment deposition and erosion patterns near the diversion intake, flushing channel, and hardened ramp fish entrance and exit.
- Evaluate hydraulic conditions, flow distribution and flow patterns near the diversion intake, flushing channel, and hardened ramp fish exit
- Observe fishway attraction flows and entrance conditions downstream of the hardened ramp.

MOD-6 Versus MOD-9

The main differences in these design configurations are the elevation of the upstream end of the hardened ramp, the length of the hardened ramp, the elevation of the sill of the canal intake, and elevations and extents of a notch made into the existing dam crest. Elevations for both configurations are compared in Table 8. The difference in extents of the notch in the dam crest is shown in Figure 26. Dimensions and elevations of the MOD-9 notch are shown for the 1:12 model in Figure 27.

Table 8. Elevations for hardened ramp alternatives MOD-6 and MOD-9.

Structure/Feature	***MOD-6***	***MOD-9***	***Notes***
Apron	154.0	154.0	
Sill Invert	156.0	156.5	
Flushing Channel Invert	154.0	154.0	
Hardened Ramp Invert - Gate 1	154.5	156.5	
Hardened Ramp Invert - Gate 2	155.0	157.0	
Hardened Ramp Invert - Gate 3	157.3	159.3	
Hardened Ramp Invert - Gate 4	158.0	160.0	
Top of Ramp Wall	166.0	166.0	
Dam Crest Notch	160.5	161.5	MOD-6 notch extends 400 ft from the ramp wall out of the model extents. MOD-9 notch extends 100 ft from the ramp wall
Dam Crest	N/A	162.0	Model extents for MOD-6 do not include the existing elevation of the dam crest.

Figure 26. Dam crest configuration comparing MOD-6 (400 ft notch) to MOD-9 (100 ft notch) design configurations in 1:24 model.

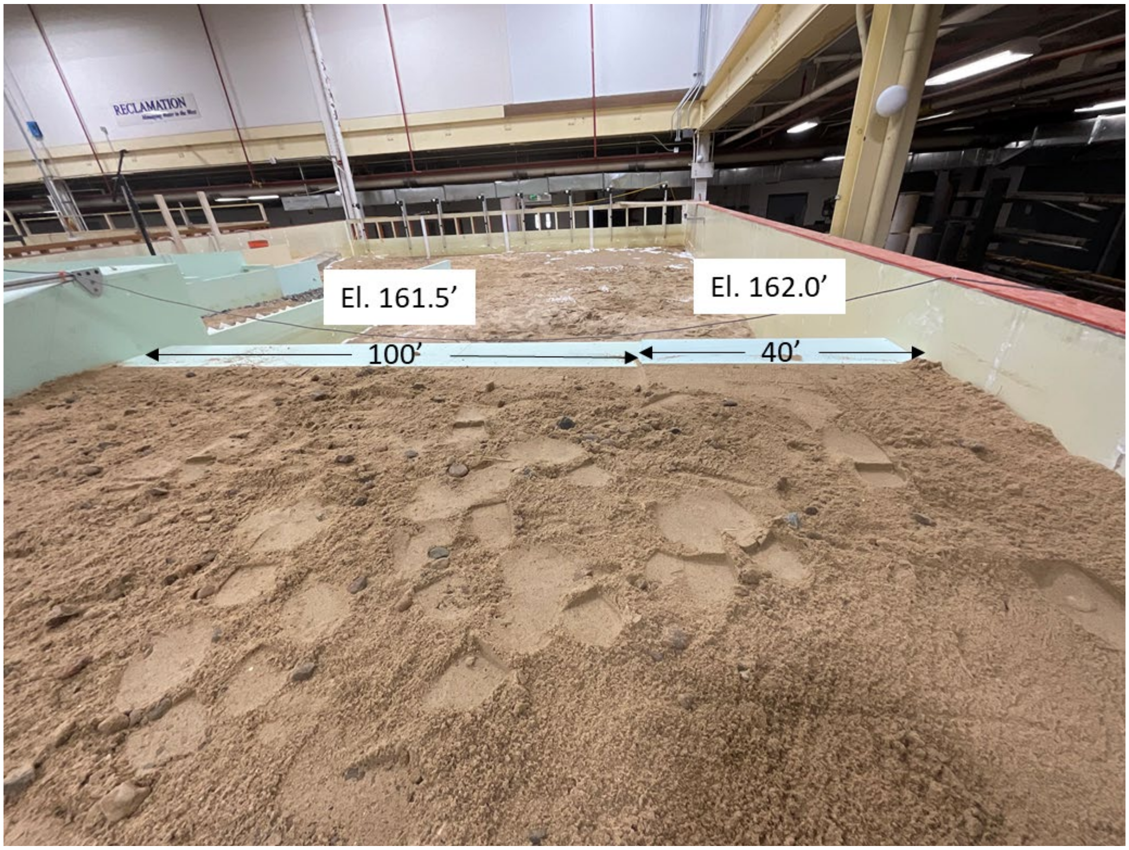


Figure 27. The 100-ft notch in the crest for the MOD-9 configuration in the 1:12 scale model. The hardened ramp was extended about 38 ft downstream to maintain the same slope of 5% and downstream invert elevation of 134.0 ft. This modification in the 1:12 model is shown in Figure 28.

Figure 28. Photograph showing the 38-ft downstream extension of the hardened ramp in the 1:12 scale model for the MOD-9 design configuration.

1:24 Baseline Testing

The 1:24 model included the baseline river topography upstream, 300 ft of the dam crest, the hardened ramp structure, an adjacent flushing channel, and the canal intake structure with intake gates. During baseline testing the canal intake gates were represented by PVC sheets set at varying elevations to control overtopping flow into the canal with a target diversion discharge of 825 ft^3/s (750 ft^3/s plus 10% for fish screen return flow). Intake gates and elevations for each test configuration are shown in Figure 29 and Table 9.

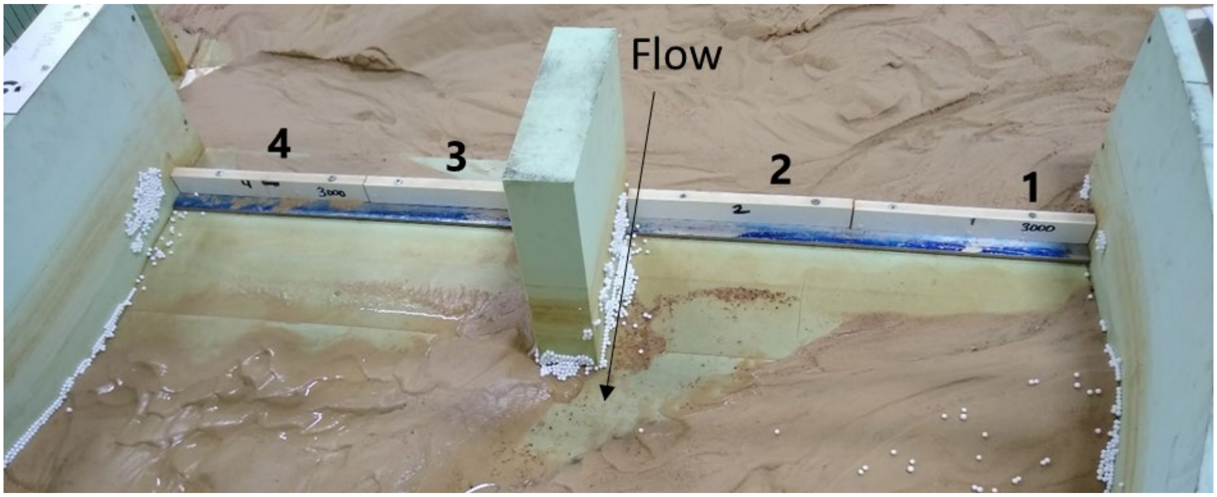


Figure 29. Intake gate settings used in the 1:24 model for baseline testing (looking upstream from canal intake).

Table 9. Intake gate elevations used for 1:24 baseline testing.

Flow (ft^3/s)	***Gate 1 (ft)***		***Gate 2 (ft)***		***Gate 3 (ft)***		***Gate 4 (ft)***	
	MOD-6	*MOD-9*	*MOD-6*	*MOD-9*	*MOD-6*	*MOD-9*	*MOD-6*	*MOD-9*
3,000	158.5	159.8	158.5	160.3	158.5	160.3	158.5	160.3
6,000	159.8	161.6	159.8	161.6	159.8	162.0	159.8	162.0
Fully Closed	161.0	162.8	161.0	162.8	161.0	162.8	161.0	162.8

Baseline model testing of the MOD-6 and MOD-9 designs was completed at 3,000, 6,000, 12,000, and 30,000 ft^3/s The model was run to quasi-steady state flow conditions with sediment-laden water recirculated with the pump system. The model was watered up slowly to prevent bed disturbance, after which the flow was ramped up to the desired flow condition.

The flushing channel was controlled by a 15-ft-wide slide gate that was either fully open or fully closed (Figure 30). To represent the configuration with the flushing channel removed, the canal intake structure and apron were moved 20 ft into the river so that the flushing channel was blocked off. The upstream left bank topography was also shifted into the channel by 20 ft and the baseline bathymetry was adjusted accordingly. The model configurations both with and without a flushing channel are shown in Figure 34 through Figure 35.

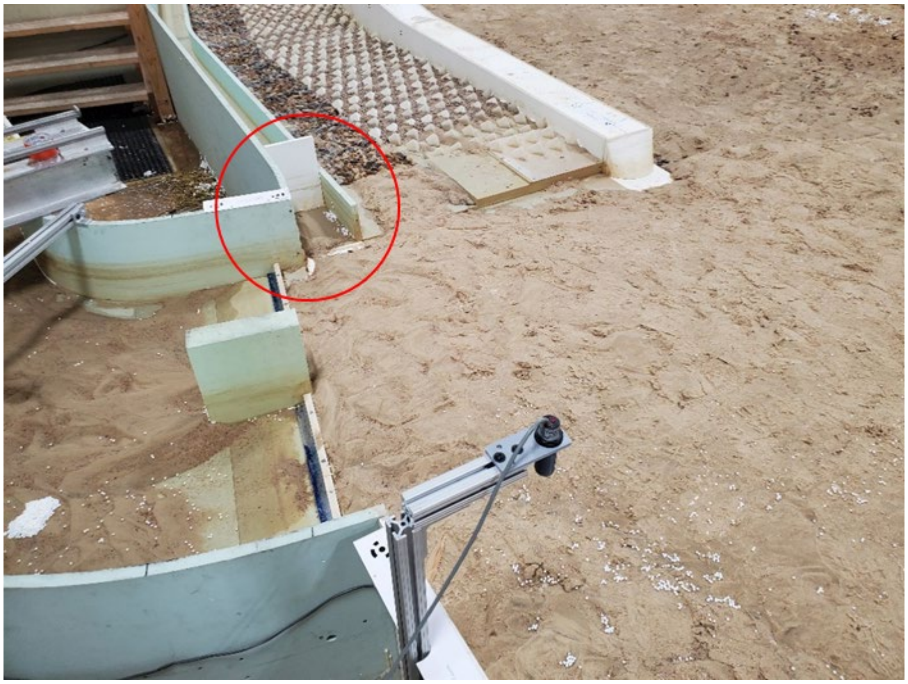


Figure 30. MOD-6 design configuration with flushing channel installed and flushing channel gate closed.

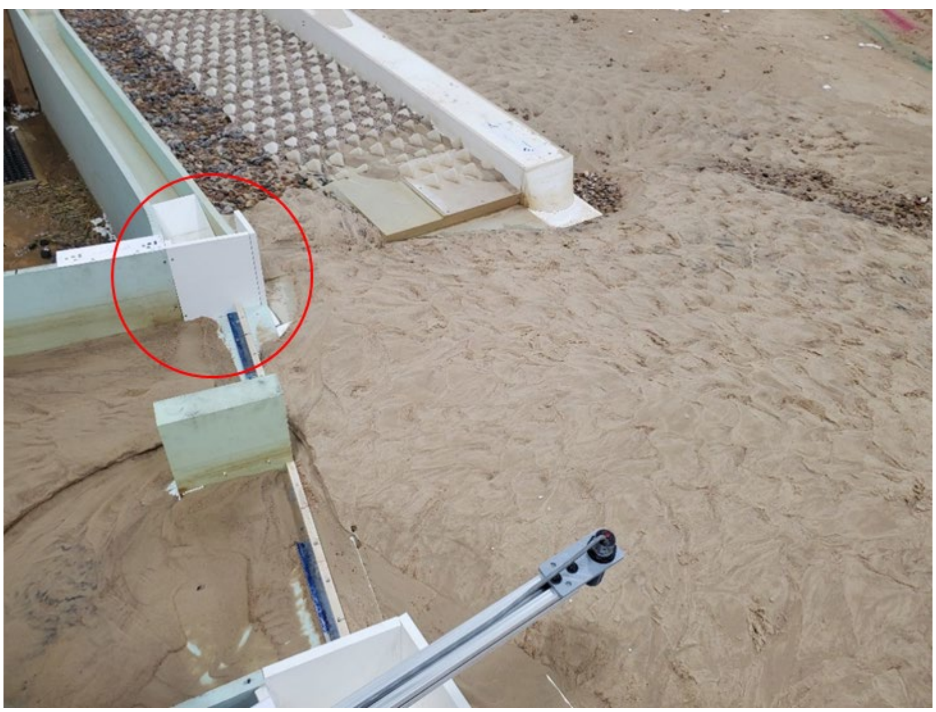


Figure 31. MOD-6 design configuration with flushing channel removed.


Figure 32. Upstream topography with flushing channel for MOD-6 design configuration.


Figure 33. Downstream topography with flushing channel installed for MOD-6 design configuration, looking upstream.

Figure 34. Upstream topography modification with flushing channel removed for MOD-6 design configuration.

Figure 35. Downstream topography modification with flushing channel removed for MOD-6 design configuration, looking upstream.

Each series of baseline tests began with the baseline river topography determined in shakedown testing and was completed for the design configuration with a flushing channel (open and closed) and without a flushing channel. Water levels and PIV velocities were collected during each test run and bed scans were made of the mobile bed areas adjacent to the upstream and downstream ends of the hardened ramp. After testing with the MOD-6 design configuration, the test series was repeated for the MOD-9 design configuration. Baseline test runs are shown in Table 10 and Table 11 in the order in which they were tested.

Note that canal diversion occurred at 3,000 and 6,000 ft^3/s, but there are no diversion flows at 12,000 and 30,000 ft^3/s. The intake gates were set to their fully closed positions (161.0 ft for MOD-6 and 162.8 ft for MOD-9) and the downstream canal control gate was closed. This allowed the gates to overtop which filled the canal intake area, but there was no active flow into the diversion.

Table 10. Test matrix for baseline testing (in testing order) of the MOD-6 hardened ramp design in the 1:24-scale physical model.

River Flow (ft^3/s)	Target Diversion Flow (ft^3/s)	Flushing Channel Operation	Model Run Time (hours)
3,000	825	Closed	4
3,000	825	Open	2
6,000	825	Closed	4
6,000	825	Open	2
12,000	0	Closed	2
12,000	0	Open	1
30,000	0	Closed	1
30,000	0	Open	½
Modified physical model – removed flushing channel			
3,000	825	Removed	4
6,000	825	Removed	4
12,000	0	Removed	2
30,000	0	Removed	1

Table 11. Test matrix for baseline testing (in testing order) of the MOD-9 hardened ramp design in the 1:24-scale physical.

River Flow (ft^3/s)	Target Diversion Flow (ft^3/s)	Flushing Channel Operation	Model Run Time (hours)
3,000	825	Removed	4
6,000	825	Removed	4
12,000	0	Removed	2
30,000	0	Removed	1
Modified physical model – added flushing channel			
3,000	825	Closed	4
3,000	825	Open	2
6,000	825	Closed	4
6,000	825	Open	2
12,000	0	Closed	2
12,000	0	Open	1
30,000	0	Closed	1
30,000	0	Open	½

1:12 Baseline testing

Similar to the 1:24 model, the 1:12 model baseline included river topography upstream, 140 ft of the dam crest, the hardened ramp structure, an adjacent flushing channel, and the canal intake structure with intake gates. During baseline testing the canal intake gates were operated with electric actuators that controlled the diversion discharge for each test (Figure 36). Gate elevation settings to set and evenly distribute the target diversion flow are shown in Table 12.

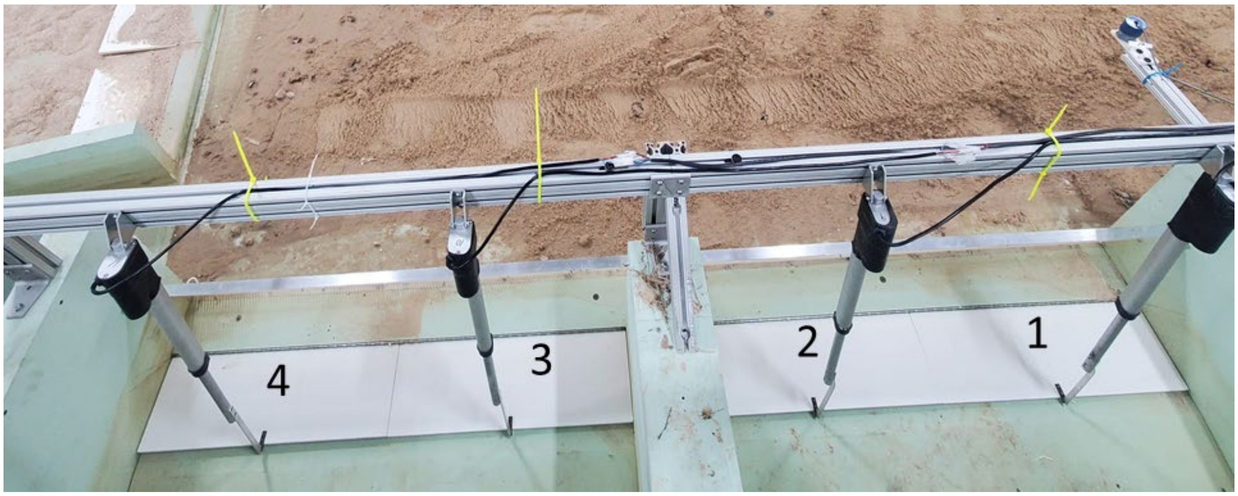


Figure 36. Canal intake gates (looking upstream from intake) with individual actuators to adjust gate settings remotely.

Table 12. Canal intake gate elevations used for diversion flows during baseline testing in the 1:12 model for both MOD-6 and MOD-9 design configurations.

Flow (ft^3/s)	***Gate 1 (ft)***		***Gate 2 (ft)***		***Gate 3 (ft)***		***Gate 4 (ft)***	
	MOD-6	*MOD-9*	*MOD-6*	*MOD-9*	*MOD-6*	*MOD-9*	*MOD-6*	*MOD-9*
6,000	160.5	162.5	160.4	162.5	160.5	162.5	160.4	162.4
3,000	159.6	161.3	159.7	161.3	159.6	161.4	159.5	161.3
1,500	156.1	159.4	156.1	159.4	156.1	159.4	156.2	159.4
270	156.1	158.7	156.1	158.8	156.1	158.8	156.2	158.8
Flushing Operations (Fully Closed)	161.0	162.8	161.0	162.8	161.0	162.8	161.0	162.8

The physical model was run at 6,000, 3,000, 1,500 and 270 ft^3/s during steady state flow conditions with sediment-laden water recirculated with the pump system. The model was watered up slowly to prevent bed disturbance after which the flow was ramped up to the desired flow condition. The decision to change the sequence of river flows was made in conjunction with United Water's engineering team, NHC, Dr. Larry Weber, the State of California Department of Fish and Wildlife, and NOAA Fisheries to represent the falling limb of a hydrograph when sediment management and fish passage are a concern.

Table 13 shows the configurations and test sequence in the 1:12 model for baseline testing starting with the MOD-6 design configuration. At the beginning of each test series the model was run at 6,000 ft^3/s for at least 6 hours to set the initial upstream bathymetry and sediment features. Water levels and PIV velocities were collected during each test run and bed scans were made of the mobile bed areas of the model after each run. Test series were repeated in the same manner for the MOD-9 design configuration. Due to similar results of sediment deposition in the area upstream of the hardened ramp and canal intake for configurations with and without a flushing channel in the 1:24 baseline testing, the configuration with the flushing channel removed was not included in the 1:12 model baseline testing.

Table 13. Test matrix for baseline testing (in testing order) of both MOD-6 and MOD-9 hardened ramp designs in the 1:12 scale physical model.

River Flow	Diversion Target	Flushing Operation	Run Time
ft^3/s	*ft^3/s*	-	*hr*
6,000	825	closed	1
3,000	825	closed	1
1,500	825	closed	2
270	110	closed	2
6,000	0	open	0.5
3,000	0	open	0.5
1,500	0	open	0.5
270	0	open	1

Design Development Configurations

Results and observations from baseline testing were used to modify the 30% design to improve sediment management and fish passage hydraulics. Many modifications were made to various components of the design. A chronological log of all modeling activities from the start of the study (Table 14) is presented to help show the process of baseline testing up to design development and the process for testing changes during design development. Configurations tested as part of the design development phase are described in the Results section.

Table 14. Modeling construction, testing, general observations, and site visit activities in chronological order from baseline testing through design development.

DATE	ACTIVITY	NOTES
	1:24 Construction and Shakedown	
June - September 2021	Construction of 1:24 model	
June 2021	Sediment transport shakedown tests in 3 ft flume	Results suggested sediment mix is transporting appropriately
September - October 2021	1:24 model shakedown testing	Added more sands to the mixture and adjusted upstream topography

DATE	ACTIVITY	NOTES
Sept 21-23, 2021	1:24 model shakedown testing - United Water laboratory visit #1	General model operation and compared model flows to drone video at Freeman Dam
October 13, 2021	Dr. Larry Weber - independent site visit	Overview of 1:24 shakedown testing ahead of first agency visit
October 26-27, 2021	Agency site visit #1	Overview of 1:24 model and initial findings, near end of shakedown testing
	1:24 Baseline	
November 2021	Further 1:24 bathymetry adjustments	Adjusted upstream bathymetry based on recommendations from United Water and Dr. Larry Weber
	1:24 baseline testing - MOD6	
December 2021	1:24 baseline testing - MOD9	Flow and sediment patterns very similar for both MOD 6 and MOD9, sediment stabilization takes longer at MOD9
January 2022	1:24 baseline data processing and draft summary document submitted	
January 5-7, 2022	United Water laboratory Visit #2	Witness test of 1:24 baseline test results, ran longer duration MOD9 test to see if bedform is same
Feb 6 and 9, 2022	Meeting to present 1:24 baseline test results	
	1:12 Construction and Shakedown	
October 2021 - February 2022	Construction of 1:12 model	
March 2022	Shakedown testing of 1:12 model	Compared hydraulic data and general sediment patterns to 1:24 model to confirm model performance
	1:12 Baseline	
April 2022	1:12 Baseline Testing - MOD6	Changed test procedure to test from 6,000 ft^3/s to 270 ft^3/s, more representative of falling limb of the hydrograph
	1:12 Baseline Testing - MOD9	Flow and sediment patterns very similar for both MOD 6 and MOD9
May 3-4, 2022	United Water laboratory visit #3	1:12 baseline testing demonstration and further development of flushing and training wall configurations
May 24-25, 2022	Agency site visit #2	Focused on 1:12 baseline testing demonstration and initial desander concept
	Design Development	
May 2022	Desander version 1 design and construction	Included only the desander portion of the intake without the sluicing culvert or channel
June 2022	Desander version 1 testing	Tested desander version 1 with sediment sluicing rates

DATE	ACTIVITY	NOTES
	Extended hardened ramp wall bullnose testing in 1:24 and 1:12 models	Reduced separation off the hardened ramp wall, allowing more streamlined flow for fish exiting the ramp
July 2022	Hardened ramp upstream roughness testing in 1:12 model	Compared surface roughness covering the upstream end of the hardened ramp, showed no significant difference
	Upstream river training works testing (groynes)	No significant difference in hydraulic and sediment results with groynes along left bank
	Desander version 2 design and construction	Included updated desander with single guide walls and sluicing culvert and channel downstream
August 2022	Desander version 2 testing	Desander upgrades effective, but more streamlined flow needed in culvert for improved downstream fish passage and sediment transport
August 15-17, 2022	Agency site visit #3	Focused on version 2 of desander and sluicing system in 1:24 model and observed fish passage feature concepts in 1:12 model
August 2022	1:12 low flow channel testing	PIV and point measurements of full fish features on 1:12 model hardened ramp
	No flushing channel tests with sediment features	Intake in line with left wall of hardened ramp, tested with and without sediment features, some differences but little change to general bed load deposition
September 2022	Desander version 3 design and construction	
	Desander version 3 testing	More streamlined flow conditions within the culvert, intake gate modulation needed to keep sluice cleared for tailwater elevations above 145 ft
October 2022	Flushing channel with castle training wall testing	Effective flushing and improved passageway for fish along training wall at low flow conditions
October 3-5, 2022	Agency site visit #4	Demonstration of version 3 of the desander, low flow section of hardened ramp, and castle training wall

Results

Baseline Testing

Results from Baseline testing are presented in Appendix B for the 1:24 model and in Appendix C for the 1:12 model.

In general, test results and observations showed no major differences in flow conditions approaching, exiting and within the hardened ramp between the MOD-6 and MOD-9 design configurations. A large sediment bedform consistently developed in front of the intake for both MOD-6 and MOD-9, causing large amounts of sediment to enter the diversion. The bedform could not be removed by operating the flushing channel. Flow conditions within the baffled section of the hardened ramp were considered satisfactory; but hydraulics in the low flow channel section could be improved. A common result from all test configurations at discharges greater than 1,500 ft^3/s was a shear zone that developed from the right wall of the hardened ramp and cross flows approaching the upstream end of the hardened ramp.

Flow streamlines approaching the hardened ramp were similar for both design configurations as well as flow splits between the dam and hardened ramp. The main difference was water surface elevations at the upstream side of the diversion intake which were higher for MOD-9. Due to the lower water levels at the intake for MOD-6, this configuration was not capable of achieving the target diversion flows for river flow test conditions of 270 and 1,500 ft^3/s.

Design Development

Results from Baseline Testing influenced the subsequent design development testing in the following ways:

- Since hydraulics approaching and exiting the hardened ramp were similar for both MOD-6 and MOD-9 design configurations, except for MOD-6 not being able to achieve target diversion flows for river flow conditions less than 1,500 ft^3/s, design development focused on the MOD-9 configuration.
- Since large amounts of sediment were continuously ingested into the canal intake, a desander structure was tested in the 1:24 model to trap and remove sediment that passed over the intake crest gates.
- The low flow section of the hardened ramp needed reduced velocities and more diversity of fish passage routes, so additional rock placements were tested in the 1:12 model.
- Since operation of the flushing channel was ineffective in removing sediment, a training wall intended to concentrate flow and increase flushing efficiency was introduced and tested in both scale models.
- Due to the significant flow separation observed from the bullnose on the right ramp wall, the wall and bullnose were extended farther upstream for a more direct flow approach to the hardened ramp was tested in both scale models for all remaining testing during the design development phase.

Sediment Management

Hardened Ramp Wall Bullnose - description

The first modification to the design was to extend the right wall of the hardened ramp upstream 80 ft and add a fully rounded shape (bullnose) to the end in both the 1:24 and 1:12 models. Details are shown in Figure 37 and Figure 38 compared to the original design. This modification was maintained as other design changes were made throughout the design development phase.

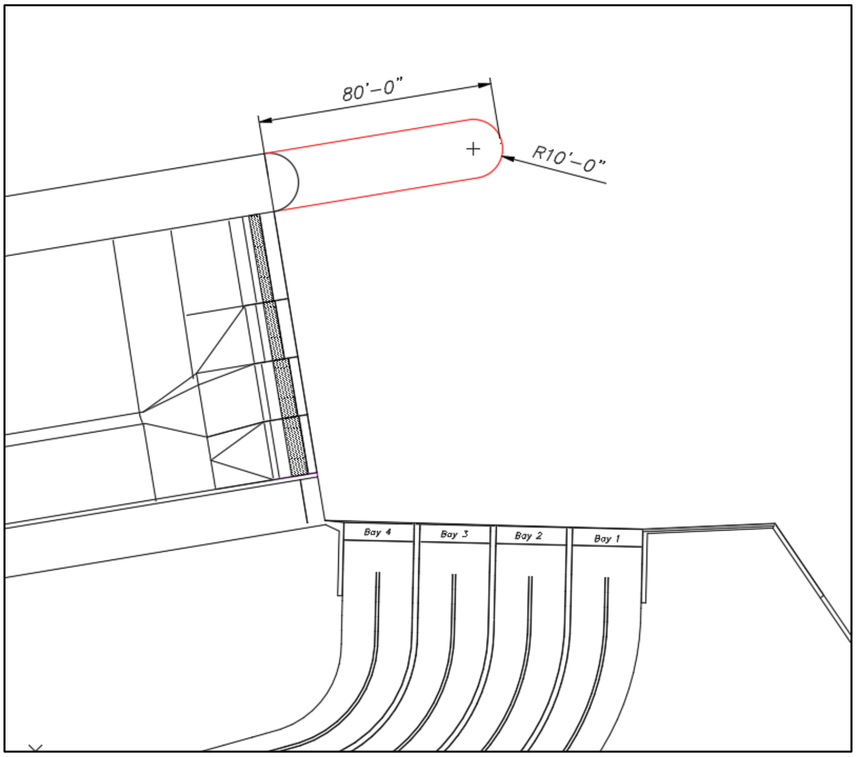


Figure 37. Layout showing the extension of the hardened ramp wall and bullnose.

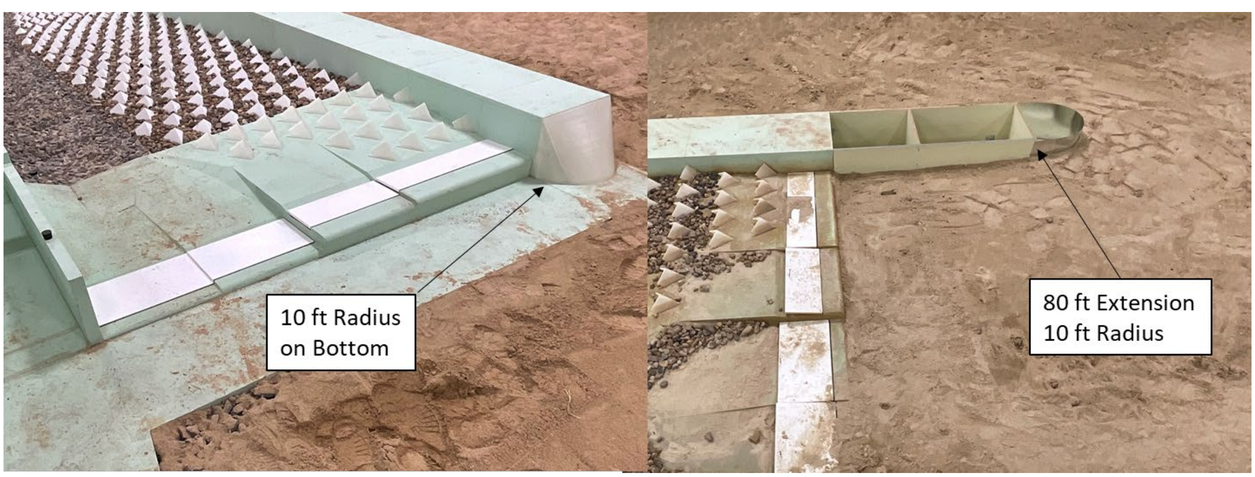


Figure 38. Photographs of the 1:12 physical model comparing the original design of the bullnose for baseline testing (left) with the extension tested in the design development phase (right).

No Flushing Channel Configuration – Test Description

Two design configurations without a flushing channel were tested in the design development phase in the 1:24 model. The first configuration was considered an initial control to be compared to the second configuration and included the extension of the hardened ramp right wall bullnose and the rotation of the canal intake so that the sill was parallel to the hardened ramp walls. The second design configuration included sediment features shown in Figure 40 and Figure 41. These added sediment features included four triangular shaped piers along the canal intake that protruded 10 ft from the canal intake trash rack. Also, a sloped vane wall that transitioned from a truncated hardened ramp wall into the flow entering the right side of the hardened ramp was tested. These features were installed to promote turbulence and sediment scour locally near the canal intake and right wall of the hardened ramp to help promote sediment clearing and provide additional flow diversity for fish exiting the hardened ramp.

Tests began at 6,000 ft^3/s to allow the upstream sediment bedforms to fully develop and were then followed by 3,000 and 1,500 ft^3/s. Tests were repeated with sediment features added to the model. Velocities and flow depths were measured at each of the four hardened ramp crest gates as well as PIV, flow visualization with dye, and scans of the resulting bed formations.

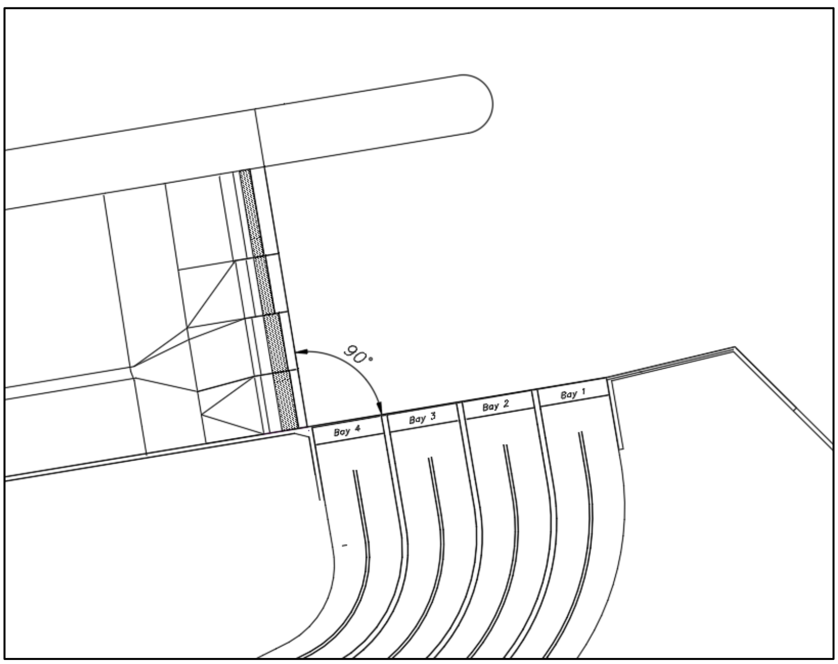


Figure 39. Layout showing an updated configuration without a flushing channel where the canal intake sill is parallel with the hardened ramp wall extension. This was an initial control configuration to be compared to added sediment features during design development testing in the 1:24 model.

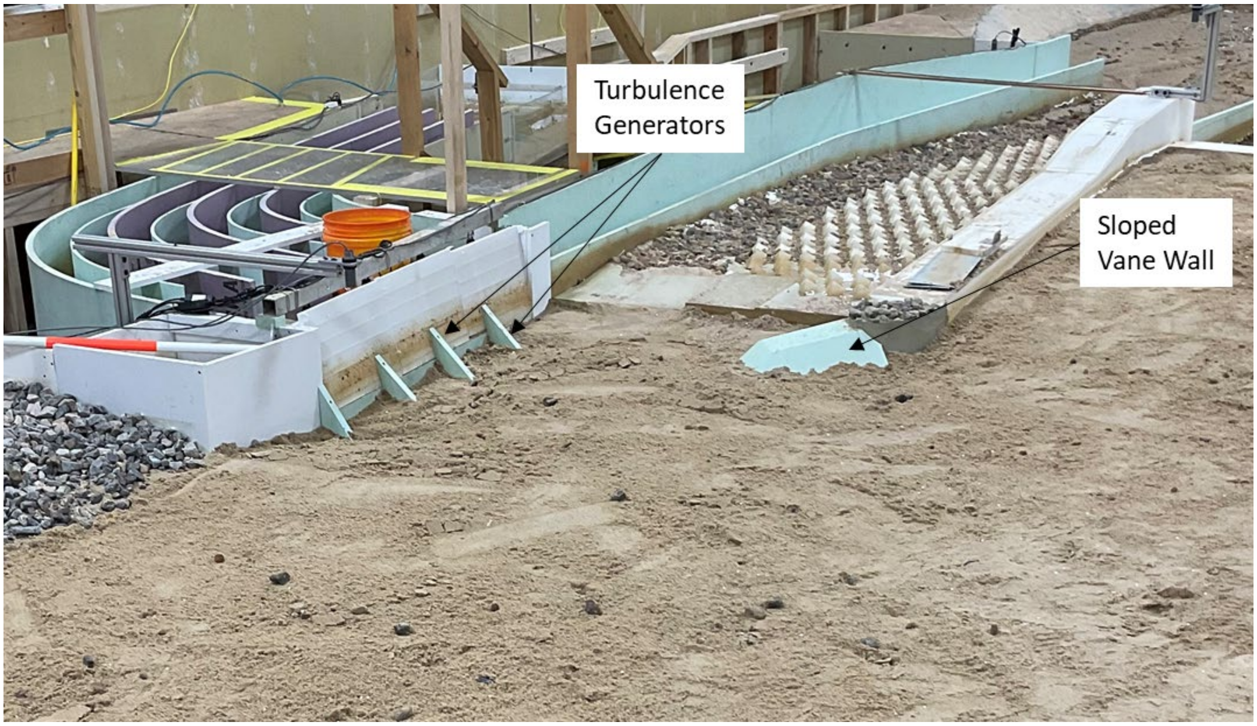


Figure 40. Photograph of the added sediment features (turbulence generators along canal intake and sloped vane wall adjacent to truncated bullnose) in the 1:24 model.

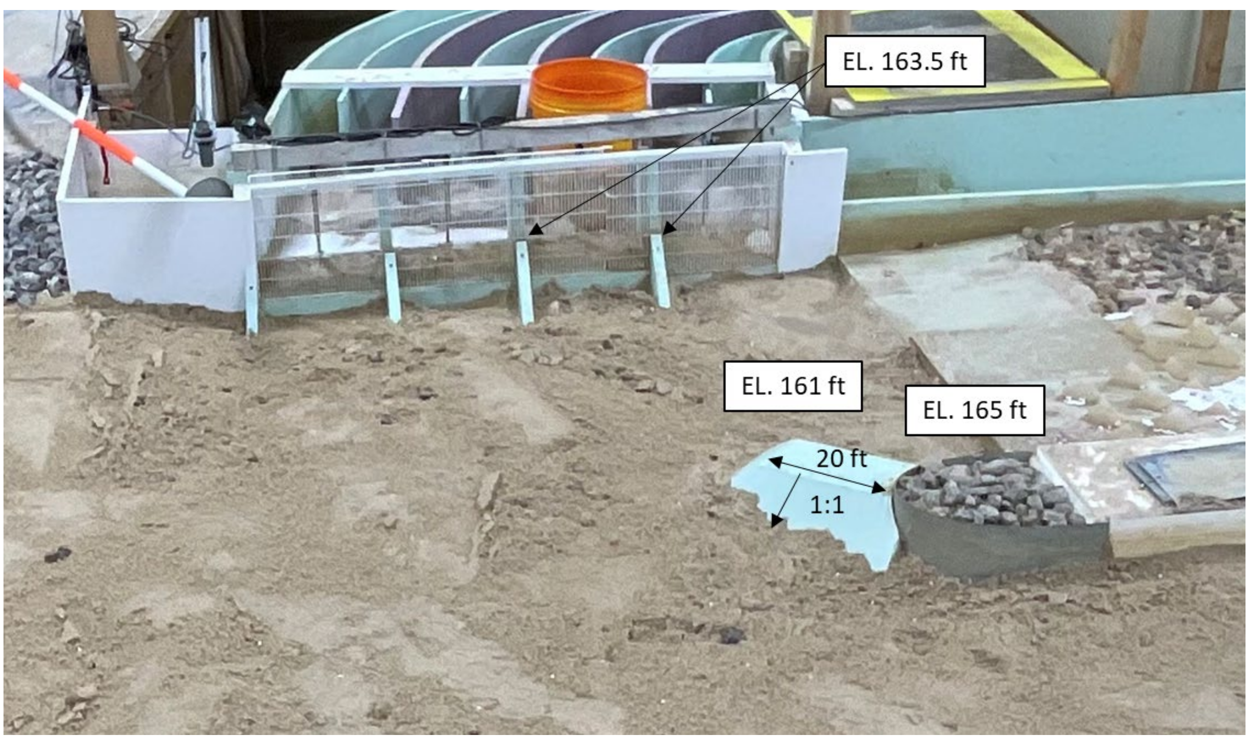


Figure 41. Photograph showing elevations and dimensions of the added sediment features in the 1:24 model.

No Flushing Channel Configuration – Test Results

A comparison of water level and discharge measurements for 6,000, 3,000, and 1,500 ft^3/s for the "no flushing channel" configuration with and without added sediment features is shown in Table 15. There was no flow over the dam crest at 1,500 ft^3/s and flow splits between the dam and hardened ramp were similar for both configurations. At 3,000 ft^3/s these flow splits showed more flow through the hardened ramp than previous results from baseline testing that were closer to a 50/50 split, likely because the thalweg of the river moved adjacent to the left bank providing a more direct flow path to the hardened ramp. A similar result is shown at 6,000 ft^3/s but the flow split became more balanced as water levels increased and utilized more of the river channel on the right side toward the dam.

Table 15. Hydraulic results for the configurations without a flushing channel.

Test Condition		**Upstream Intake**	**Dam Crest**	**River Flow**	**Diversion Flow**	**Dam Flow**	**HR Flow**
	ft^3/s	*ft*	*ft*	*ft^3/s*			
Baseline Condition	6,000	163.8	163.3	5,977	855	1,914	3,208
	3,000	162.5	162.1	3,001	840	319	1,842
	1,500		-	1,650	800	0	850
Added Sediment Features	6,000	163.5	163.2	5,993	818	1,740	3,434
	3,000	162.1	162.0	3,013	824	219	1,970
	1,500		-	1,592	768	0	825

Table 16 shows velocity and flow depth measurements at four gate locations across the hardened ramp fishway exit with and without sediment features installed. In general, there were no significant changes to hydraulic conditions at these locations by adding the sediment features upstream. Velocity differences on gate 1 of the ramp near the left wall may be a result of measuring only 1-D velocity with the Nixon meter in a location with 3-D velocity patterns. This area consistently remained clear of sediment for both configurations due to turbulence generated by the left wall offset from the trash rack upstream.

Table 16. Velocity and flow depth results from point measurements made at four hardened ramp upstream gate locations during testing without a flushing channel. The HR1 location is on the left side of the hardened ramp fishway exit and the HR4 location is on the right side of the fishway exit.

River Flow	HR Location	Baseline		Sediment Features	
		Velocity	Flow Depth	Velocity	Flow Depth
ft^3/s	-	ft/s	ft	ft/s	ft
6,000	1	8.2	8.0	4.3	7.5
	2	9.9	4.0	9.0	4.0
	3	9.0	5.0	6.8	4.3
	4	5.5	4.5	7.6	3.8
3,000	1	6.4	6.0	5.7	6.0
	2	6.7	3.0	7.6	3.8
	3	5.6	3.0	5.5	2.7
	4	2.8	2.3	3.2	2.2
1,500	1	3.4	4.5	4.9	4.5
	2	4.0	1.8	3.2	2.2
	3	2.5	1.0	1.0	1.0
	4	0.3	0.5	0.3	0.0

Observations of flow patterns with dye, PIV results, photographs, and bedform contour maps of the remaining sediment patterns for the initial no flushing configuration are shown in Figure 42 through Figure 56. These results include flows of 6,000, 3,000, and 1,500 ft^3/s. Results showed that flow approaching the hardened ramp was generally more streamlined compared to baseline results. Flow streamlines followed the left bank and curved slightly toward the left at the approach to the hardened ramp exit and canal intake. A significant bed form developed in the area upstream of and on the hardened ramp exit and canal intake. Localized scour developed upstream of the bullnose on the hardened ramp right wall and left wall connecting with the downstream sill of the intake.

6,000 ft^3/s – No Flushing Channel

Figure 42. Photograph of dye approaching the hardened ramp without a flushing channel at 6,000 ft^3/s.

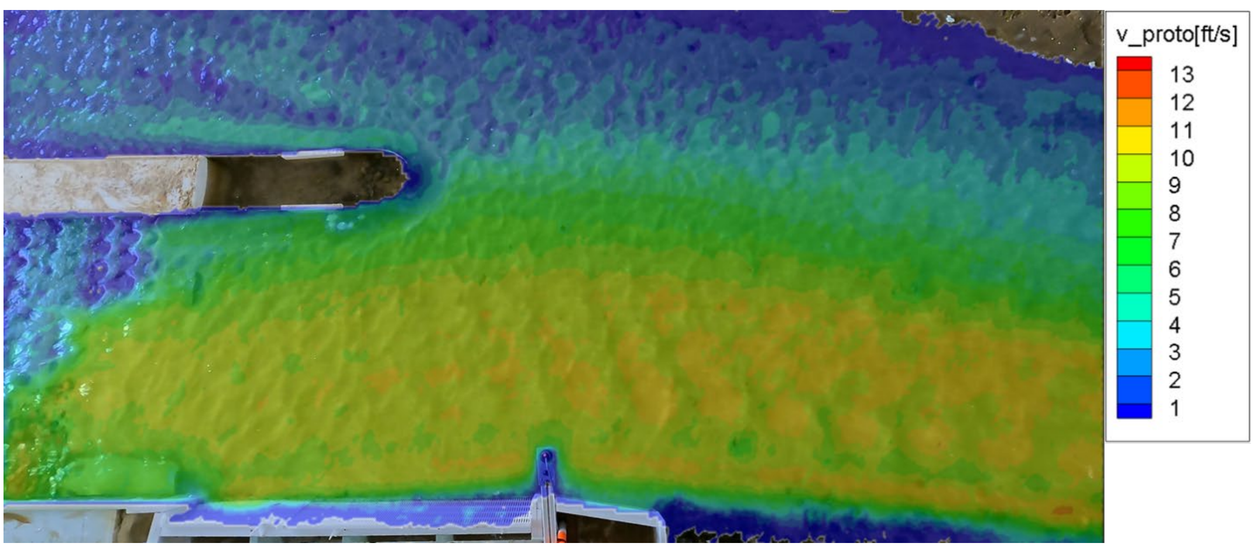


Figure 43. PIV contour plot of flow upstream of hardened ramp without a flushing channel at 6,000 ft^3/s.

Figure 44. Photographs of the sediment bedforms upstream of hardened ramp without a flushing channel at 6,000 ft^3/s.

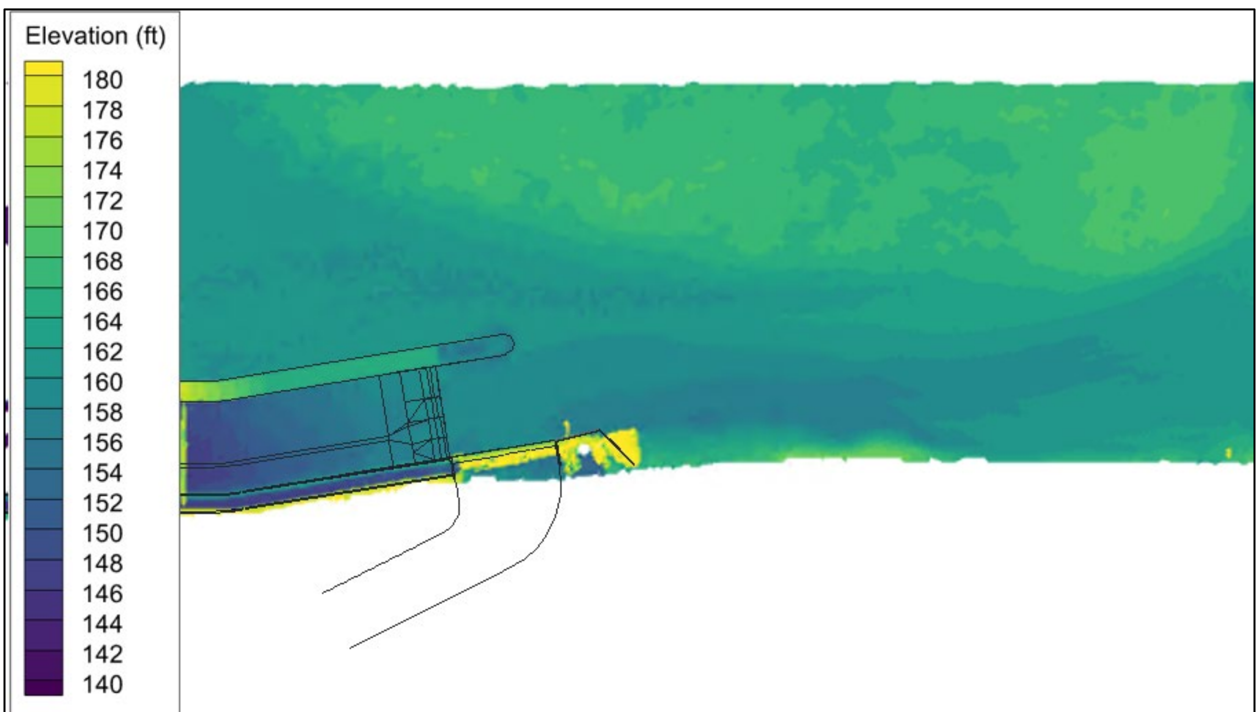


Figure 45. Color contour map of upstream bedform elevations without a flushing channel at 6,000 ft^3/s.

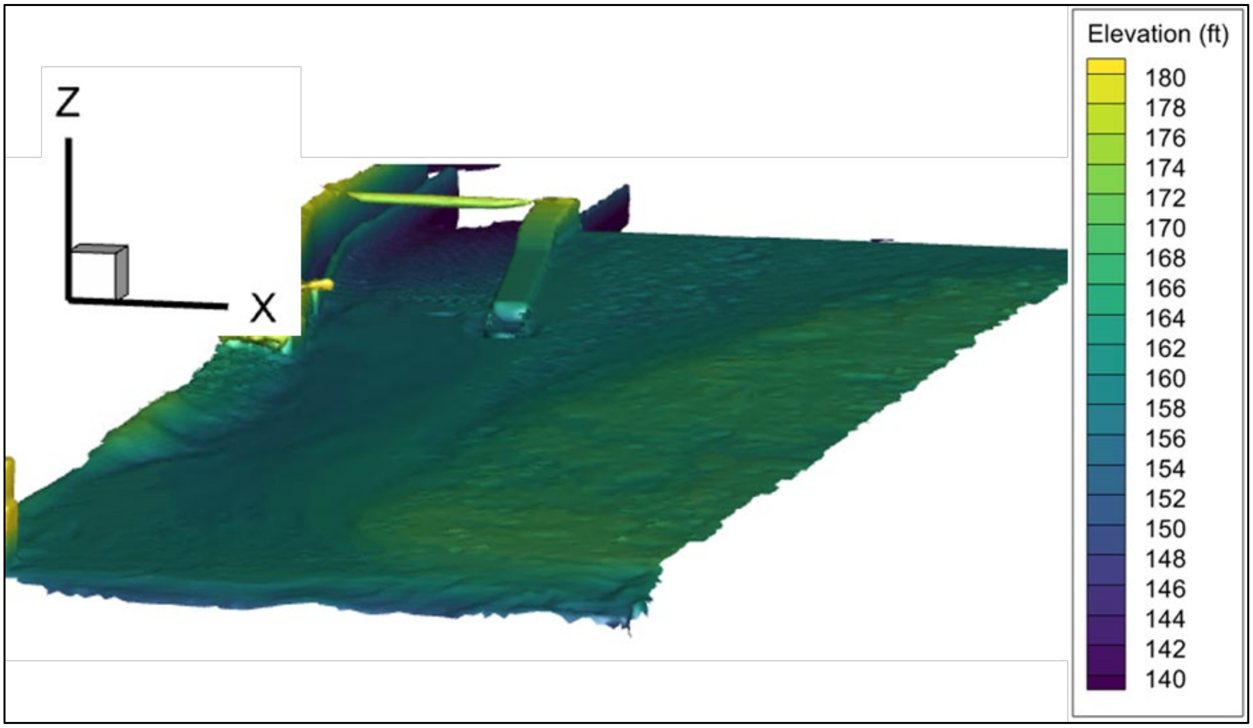


Figure 46. Isometric color contour map of upstream bedform elevations without a flushing channel at 6,000 ft^3/s. Looking downstream.

3,000 ft^3/s – No Flushing Channel


Figure 47. Photograph of dye approaching the hardened ramp without a flushing channel at 3,000 ft^3/s.

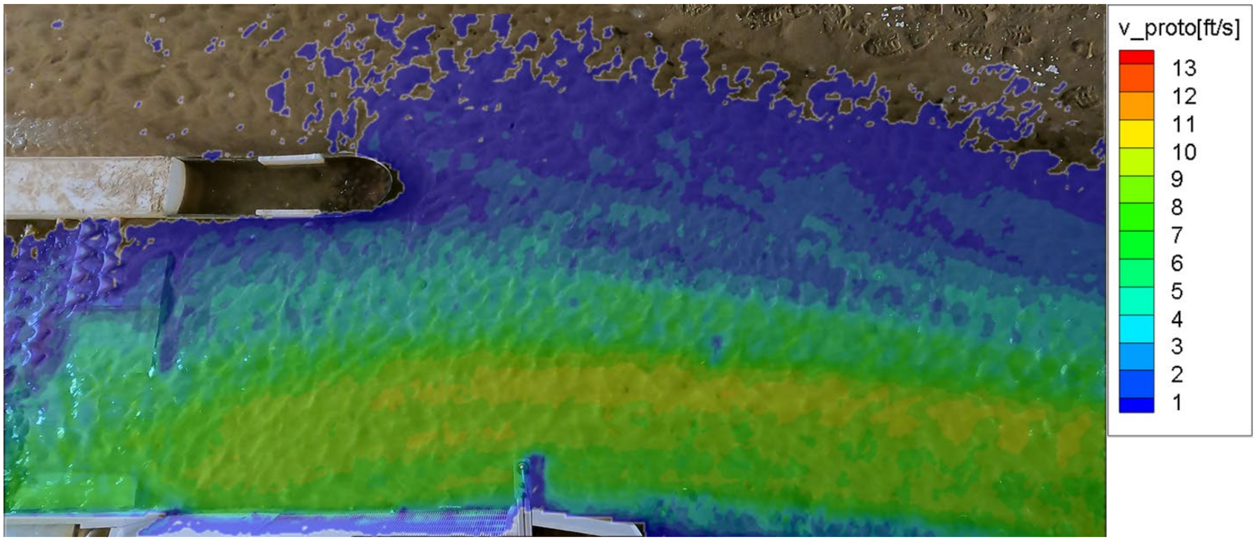


Figure 48. PIV contour plot of flow upstream of hardened ramp without a flushing channel at 3,000 ft^3/s.

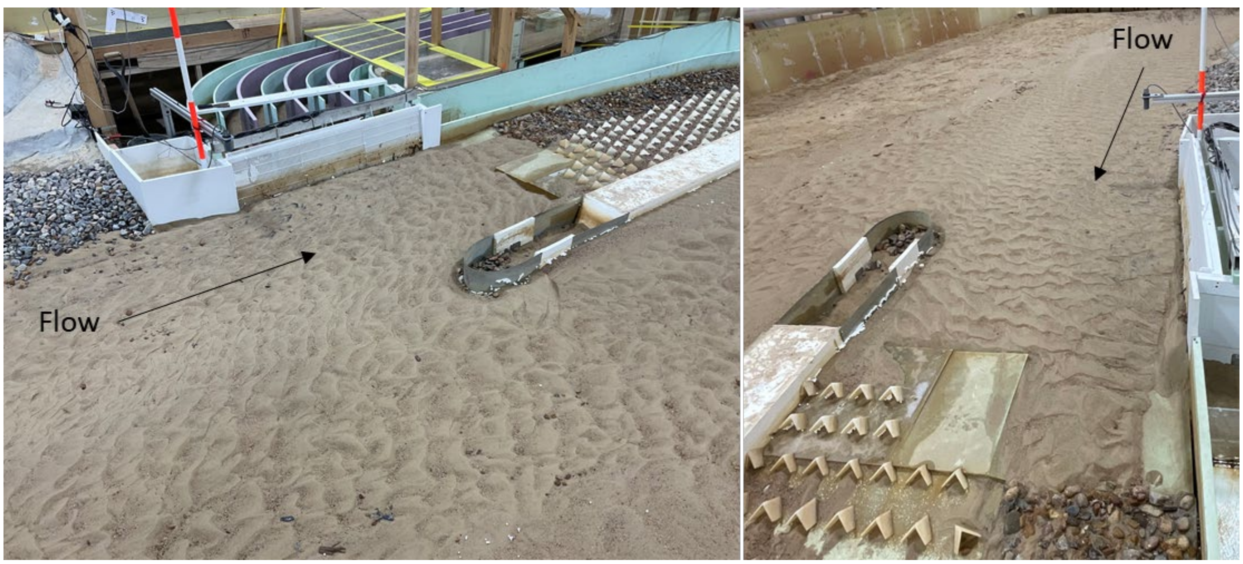


Figure 49. Photographs of the sediment bedforms upstream of hardened ramp without a flushing channel at 3,000 ft^3/s.

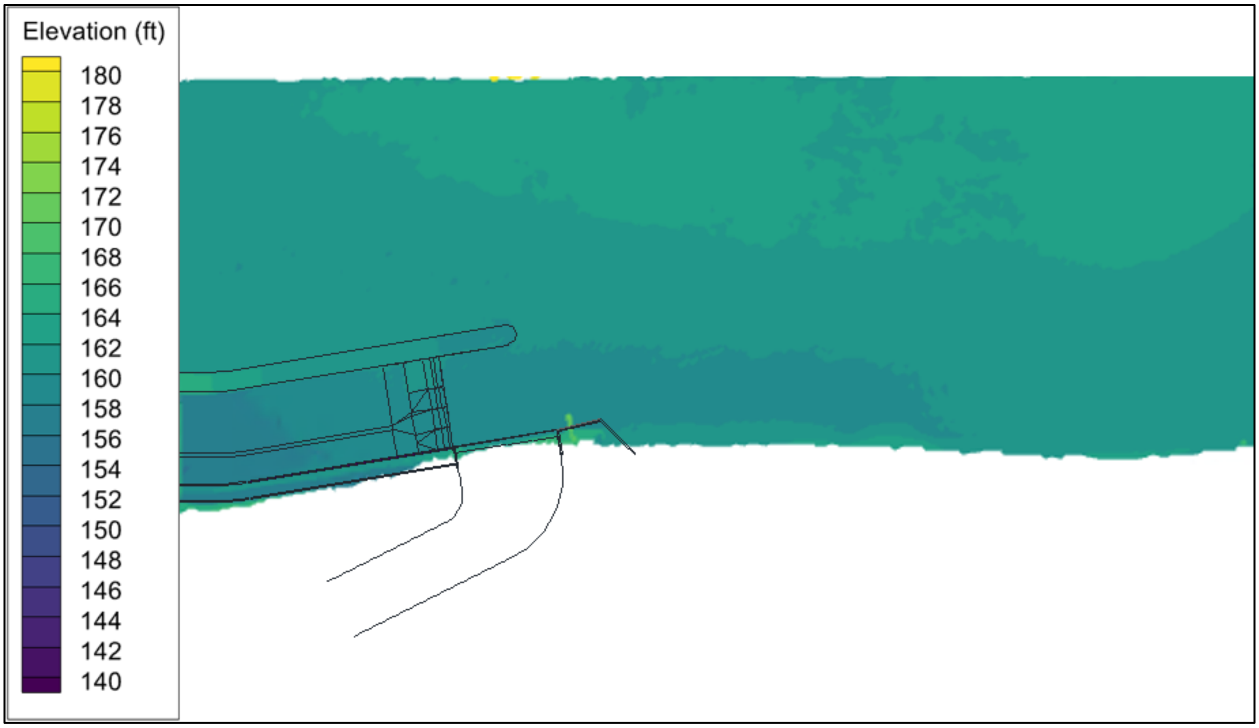


Figure 50. Color contour map of upstream bedform elevations without a flushing channel at 3,000 ft^3/s.

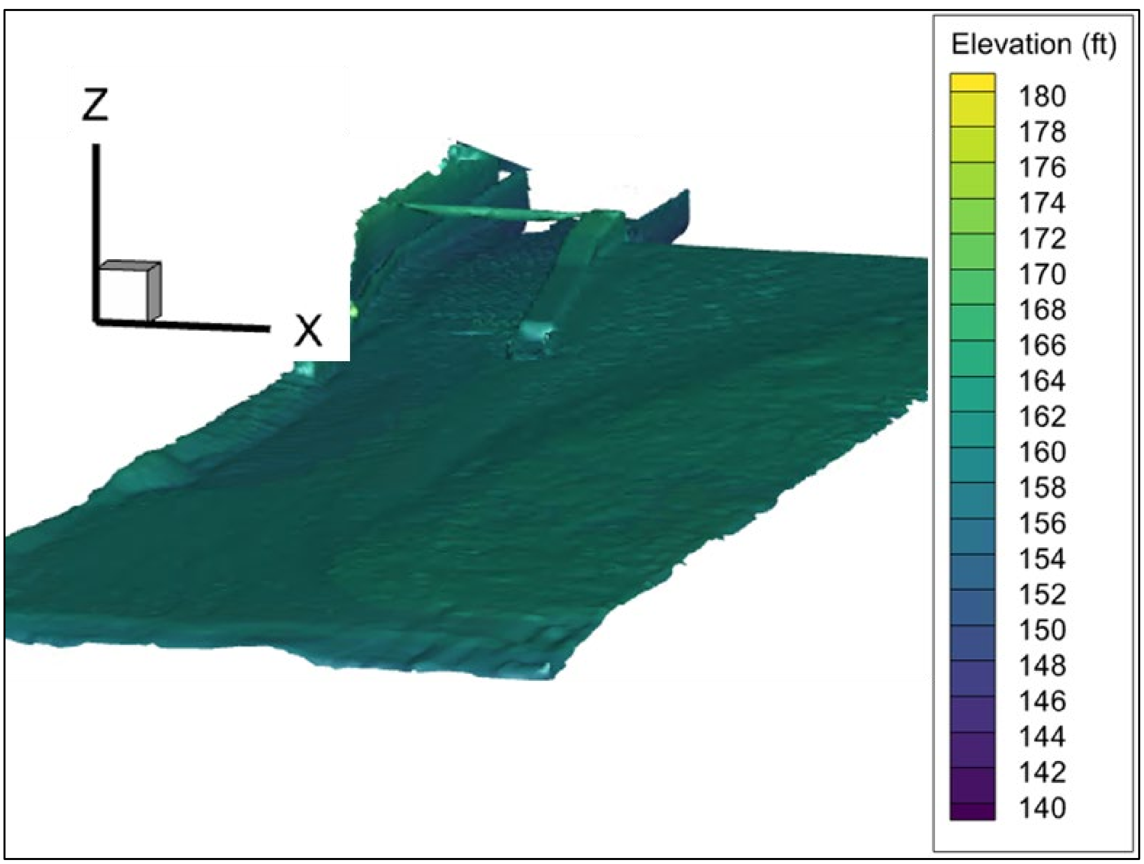


Figure 51. Isometric color contour map of upstream bedform elevations without a flushing channel at 3,000 ft^3/s. Looking downstream.

1,500 ft^3/s – No Flushing Channel

Figure 52. Photograph of dye approaching the hardened ramp without a flushing channel at 1,500 ft^3/s.

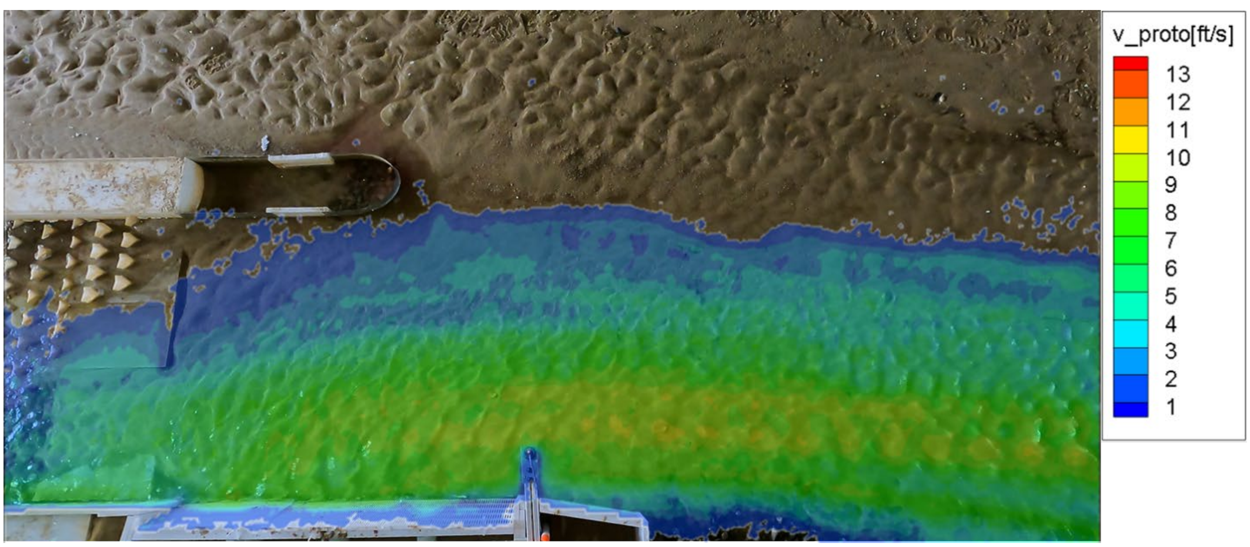


Figure 53. PIV contour plot of flow upstream of hardened ramp without a flushing channel at 1,500 ft^3/s.

Figure 54. Photographs of the sediment bedforms upstream of hardened ramp without a flushing channel at 1,500 ft^3/s.

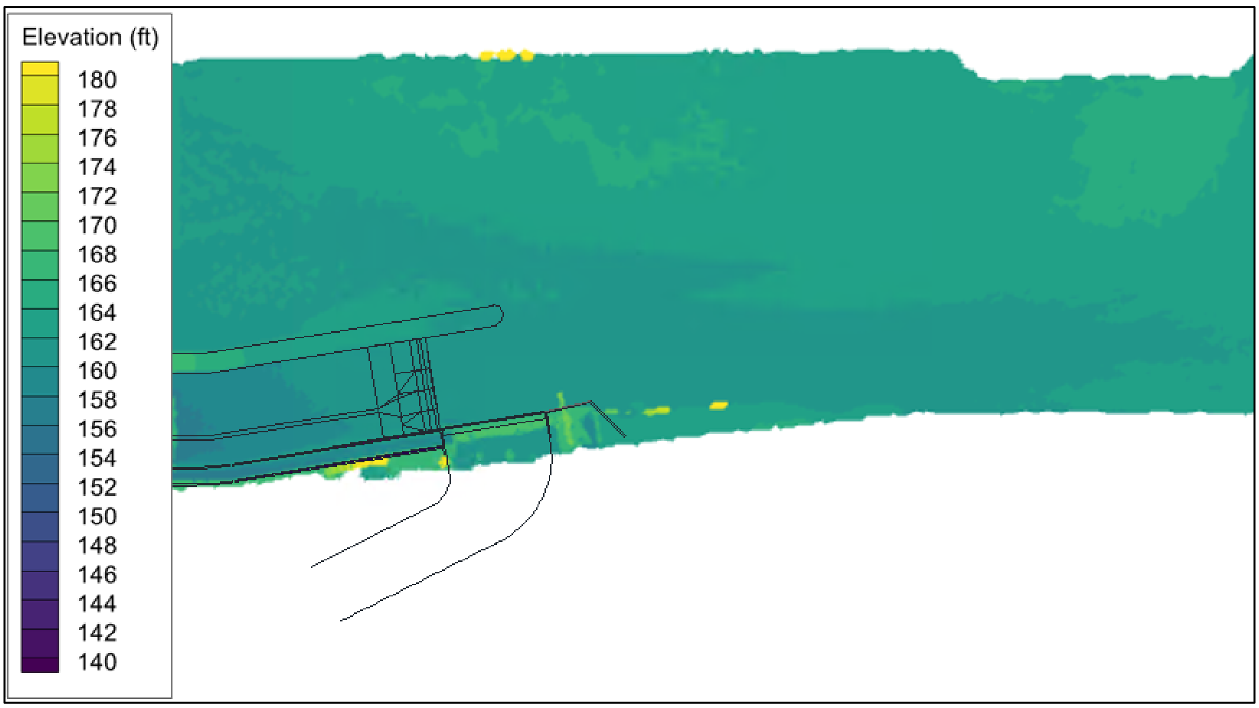


Figure 55. Color contour map of upstream bedform elevations without a flushing channel at 1,500 ft^3/s.

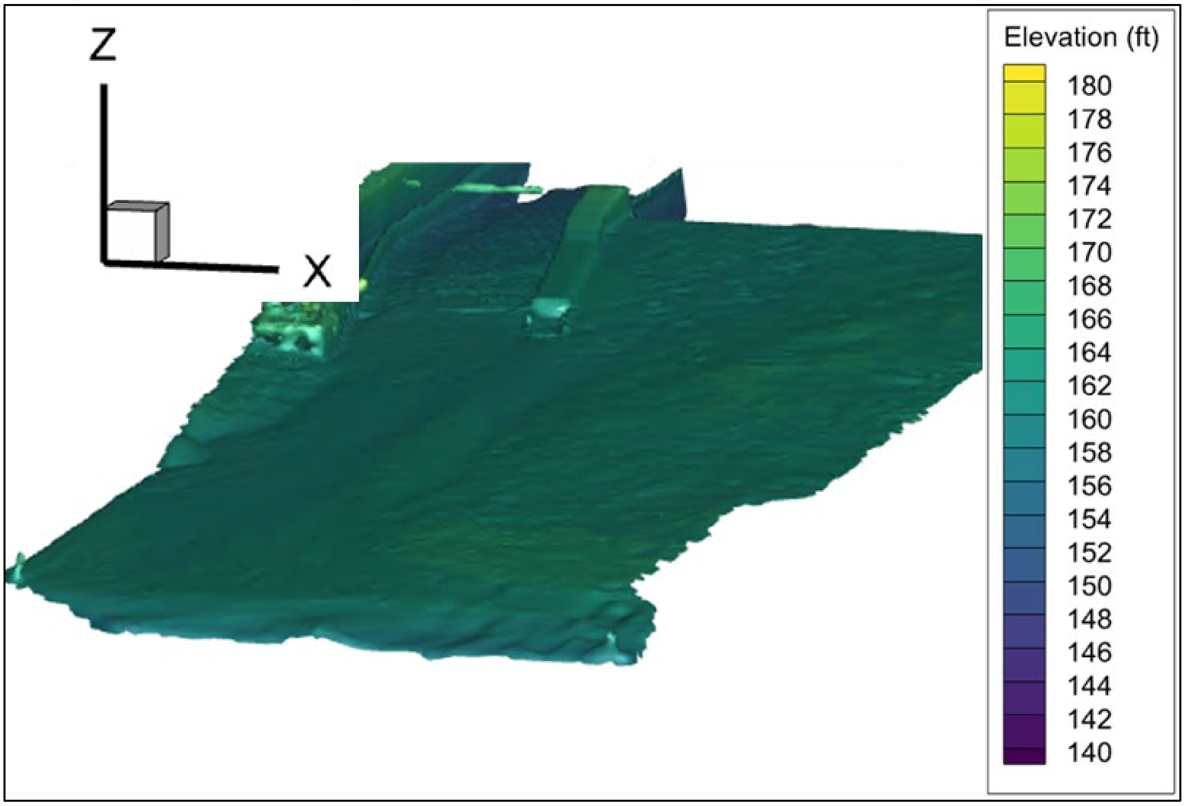


Figure 56. Isometric color contour map of upstream bedform elevations without a flushing channel at 1,500 ft^3/s. Looking downstream.

Observations of flow patterns with dye, PIV results, photographs, and bed difference maps sediment patterns for the no flushing configuration with added turbulence generators and sloped vane wall are shown in Figure 57 through Figure 68. These results include flows of 6,000, 3,000, and 1,500 ft^3/s. Similar to previous results without the sediment features, these results showed streamlined flow approaching the hardened ramp. A significant bedform developed in the same area upstream of and on the hardened ramp and canal intake.

The main difference was sand bar formation along the right side of the main flow channel approximately parallel to and upstream of the right wall bullnose. This sand bar was especially prominent at 3,000 ft^3/s which began to split the flow at a point further upstream compared to the initial test configuration (Figure 61). This feature did not have a major effect on hydraulics at the fishway exit of the hardened ramp as shown by depth and velocity measurements. Other differences include additional scour near the right side of the hardened ramp exit along the canal intake. Scour along the intake was most prominent at 1,500 ft^3/s as water levels dropped. Though not measured nor a focus of this testing, anecdotal evidence from visual observations suggested that more sediment accumulated in the canal intake with the turbulence generators located along the intake sill.

6,000 ft^3/s – No Flushing Channel with Sediment Features

Figure 57. Photograph of dye approaching the hardened ramp without a flushing channel at 6,000 ft^3/s with added sediment features.

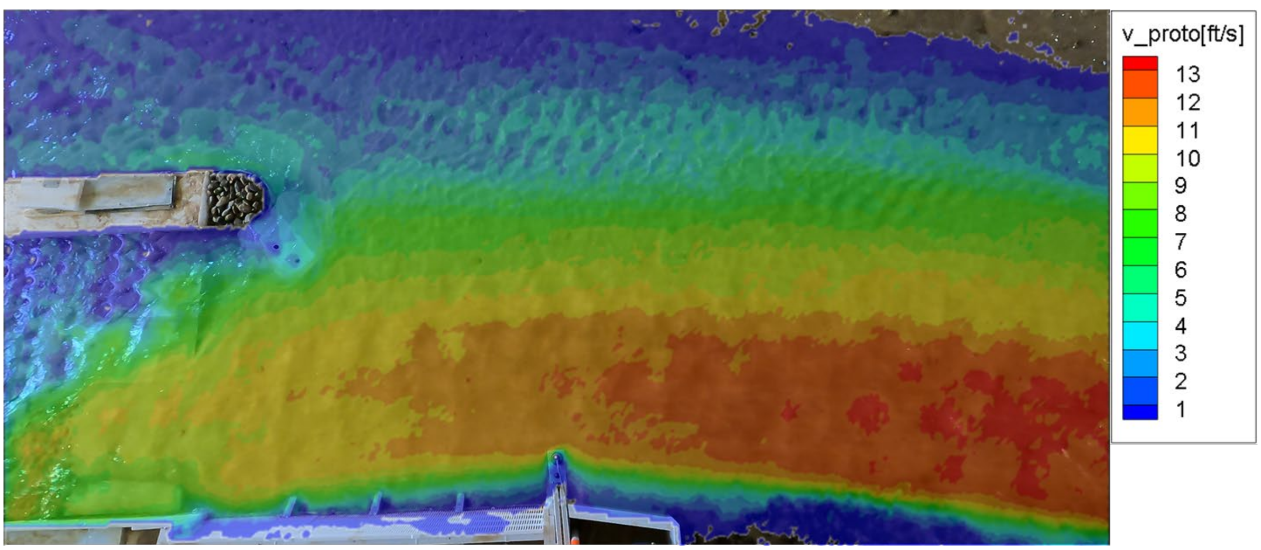


Figure 58. PIV contour plot of flow upstream of hardened ramp without a flushing channel at 6,000 ft^3/s with added sediment features.

Figure 59. Photographs of the sediment bedforms upstream of hardened ramp without a flushing channel at 6,000 ft^3/s with added sediment features.

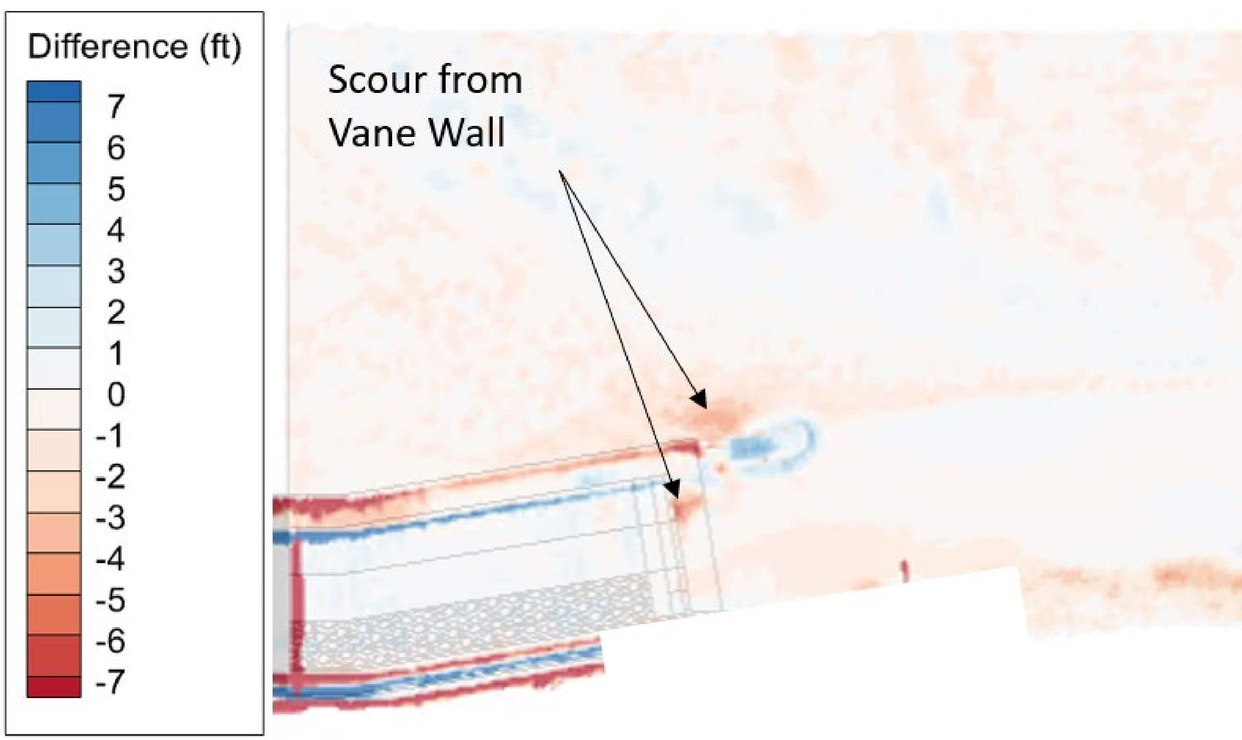


Figure 60. Color contour difference map comparing bedforms of the baseline no flushing channel configuration to the configuration with sediment features added after river discharge 6,000 ft^3/s.

3,000 ft^3/s – No Flushing Channel with Sediment Features

Figure 61. Photograph of dye approaching the hardened ramp without a flushing channel at 3,000 ft^3/s with added sediment features.

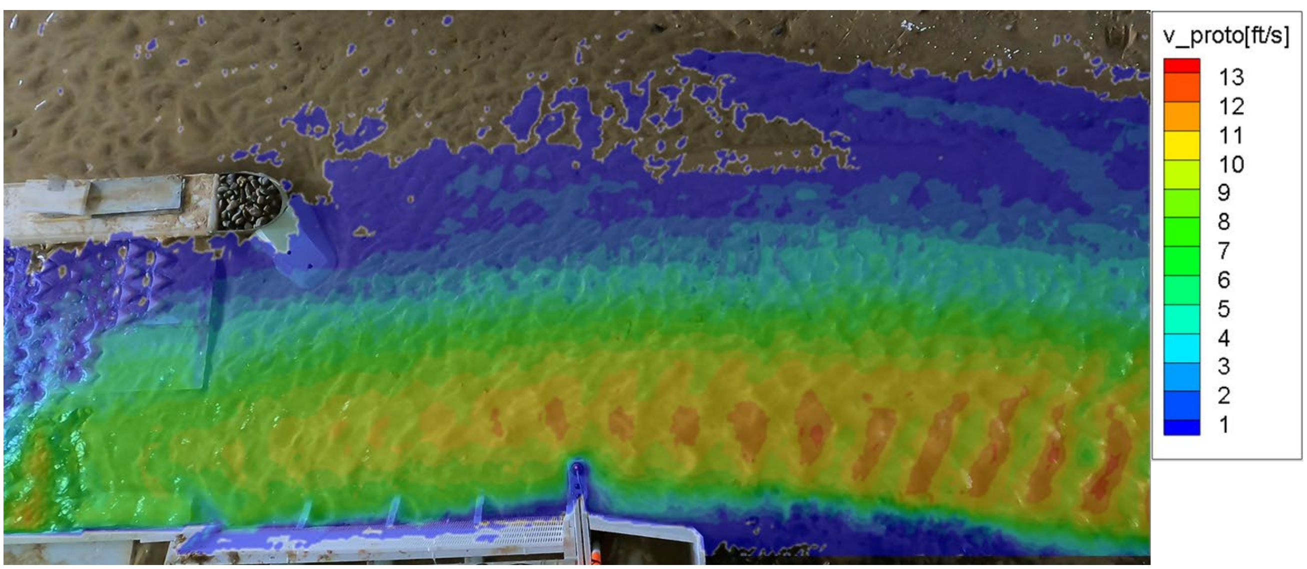


Figure 62. PIV contour plot of flow upstream of hardened ramp without a flushing channel at 3,000 ft^3/s with added sediment features.

Figure 63. Photographs of the sediment bedforms upstream of hardened ramp without a flushing channel at 3,000 ft^3/s with added sediment features

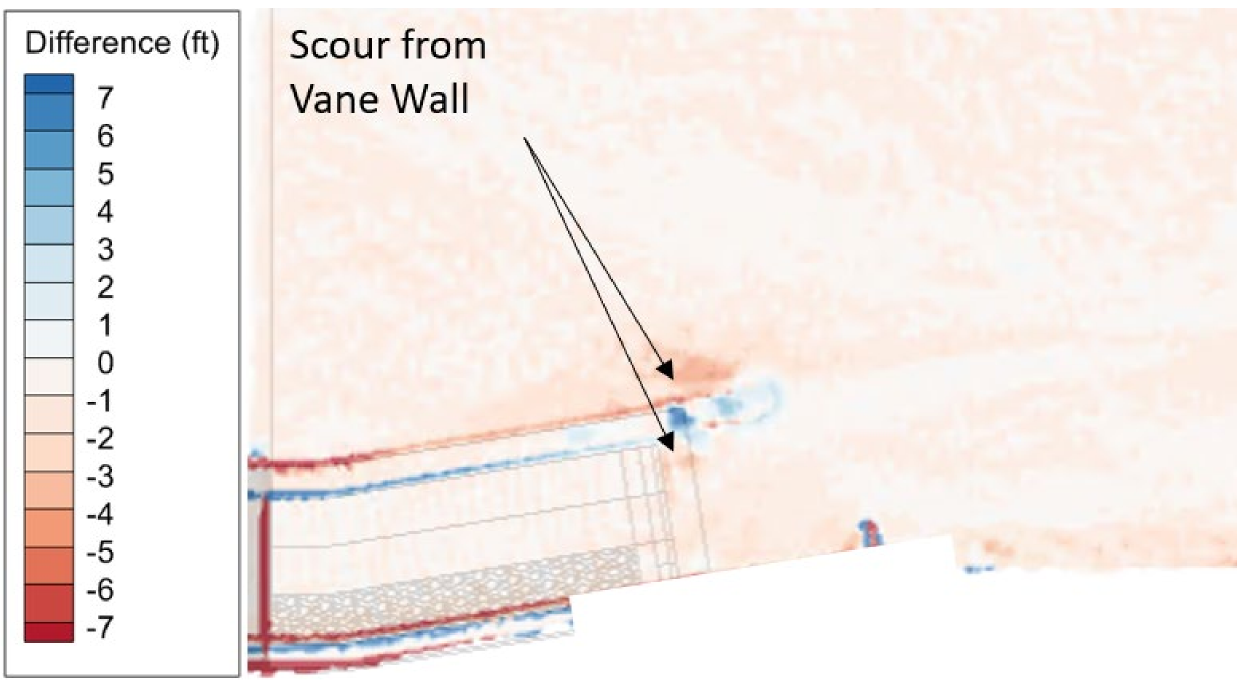


Figure 64. Color contour difference map comparing bedforms of the baseline no flushing channel configuration to the configuration with sediment features added after river discharge 3,000 ft^3/s.

1,500 ft^3/s – No Flushing Channel with Sediment Features

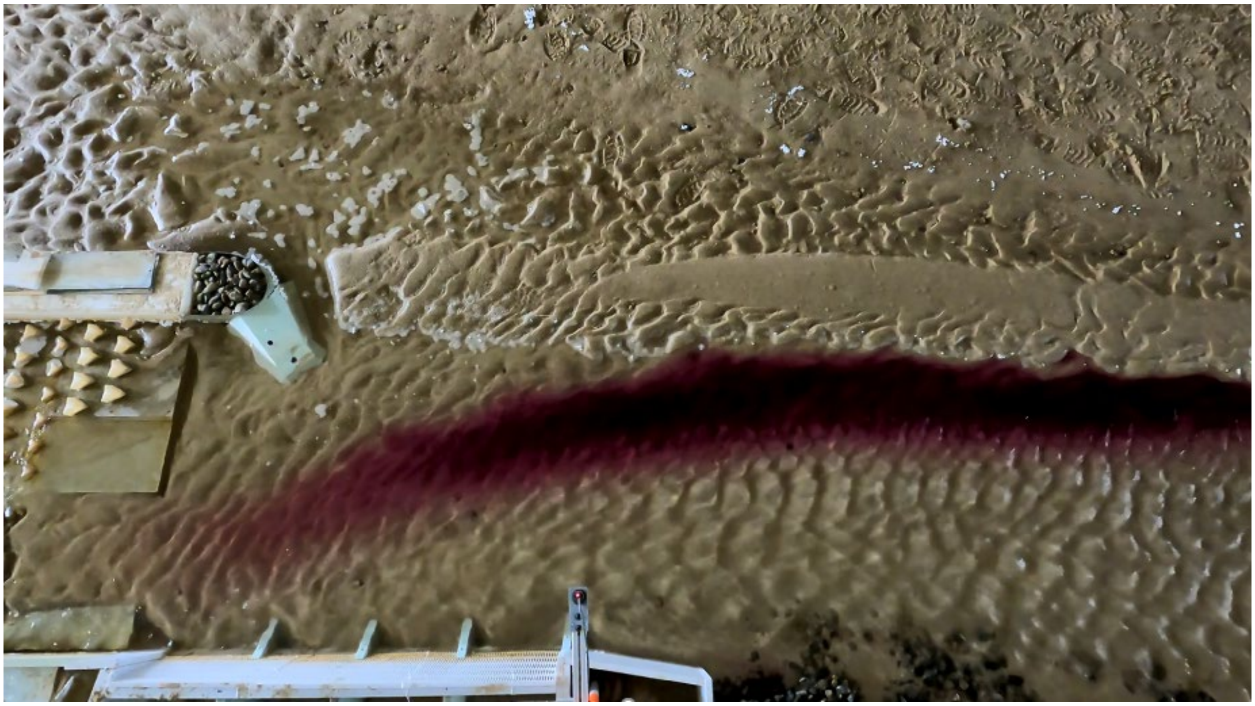


Figure 65. Photograph of dye approaching the hardened ramp without a flushing channel at 1,500 ft^3/s with added sediment features.

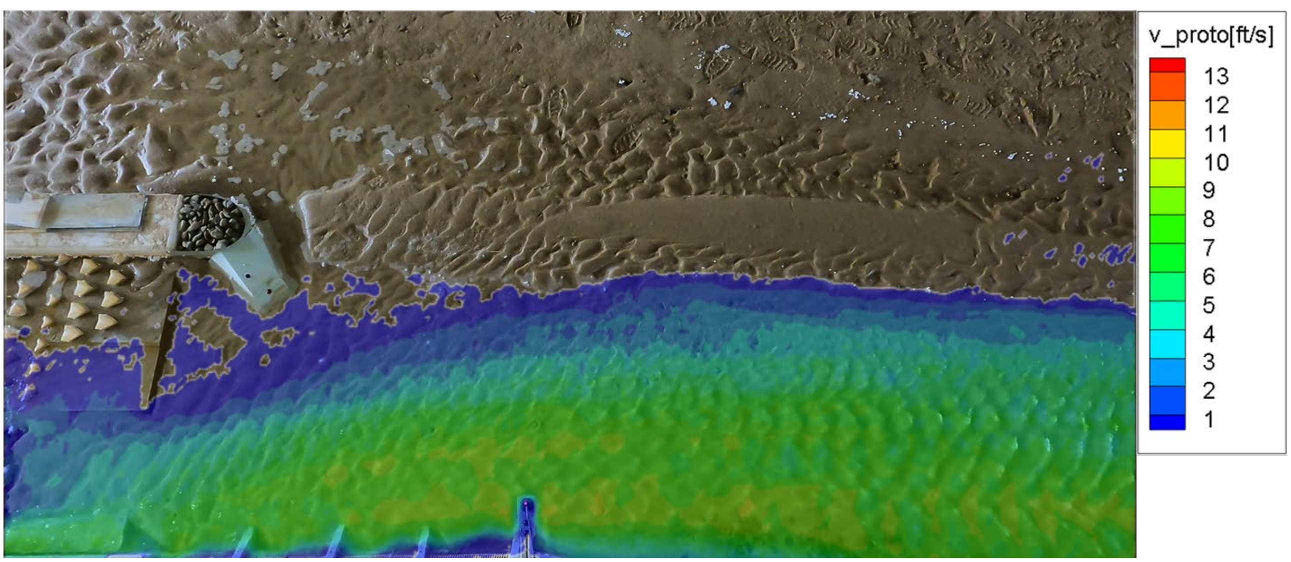


Figure 66. PIV contour plot of flow upstream of hardened ramp without a flushing channel at 1,500 ft^3/s with added sediment features.

Figure 67. Photographs of the sediment bedforms upstream of hardened ramp without a flushing channel at 1,500 ft^3/s with added sediment features.

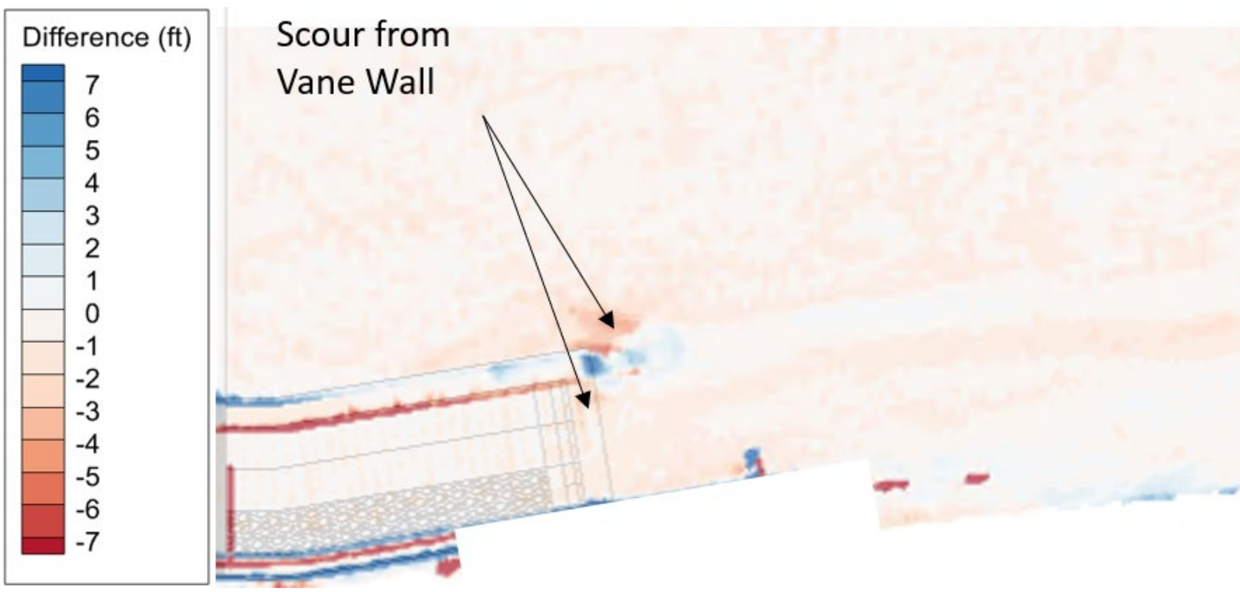


Figure 68. Color contour difference map comparing bedforms of the baseline no flushing channel configuration to the configuration with sediment features added after river discharge 1,500 ft^3/s.

While differences between the no flushing channel configurations with and without sediment features did occur locally near the sloped vane wall and turbulence generators, there was no major change to the overall sediment bedform in the area upstream and no considerable difference in hydraulics. Further testing of additional sediment features without a flushing channel was not pursued but shifted to design configurations that included a flushing channel.

Flushing Channel and Training Wall Configuration – Test Description

Tests for normal diversion operations with the latest flushing channel and castle training wall configuration (descriptions below) were performed at the same conditions and test duration as previous tests without a flushing channel. Each began at 6,000 ft^3/s to allow the upstream sediment bedforms to fully develop and were then followed by 3,000 and 1,500 ft^3/s. Velocities and flow depths were measured at each of the four hardened ramp crest gates as well as PIV, flow visualization with dye, and scans of the resulting bed formations upstream of the dam.

Three main design iterations for the flushing channel were tested in the 1:24 model, including changes to the upstream apron adjacent to the sill of the canal intake. Elevations and slopes of each version (Version 1 through Version 3) are shown in Table 17.

Table 17. Flushing channel elevations and slopes tested in the 1:24 model.

Flushing Channel Configurations				
	Invert Upstream Elevation	***Invert Downstream Elevation***	***Flushing Slope***	***Apron Slope***
Version 1	154.0	144.0	-1.5%	0.0%
Version 2	150.5	145.0	-1.1%	-2.3%
Version 3	146.0	134.0	-2.5%	-5.2%

Training wall configurations were also added to the design and tested in the 1:24 model in conjunction with flushing channel tests. Layouts and dimensions for each configuration are shown in Figure 69 through Figure 72. Each configuration included a 20-degree flare wall on the upstream end that extended approximately to the upstream end of the apron. Elevations of the top wall started low (156.5 ft) and were increased until effective flushing operations were achieved. The final tested configuration was 25-ft wide and included slots on the top as shown in Figure 72 (the "castle training wall"). The top elevation of the wall was 162 ft and the slots were 2 ft deep, except the most downstream slot which was 5.5 ft deep. The flushing channel gate was also moved upstream to where the upstream end of the left wall of the hardened ramp meets the downstream end of the training wall to prevent areas of stagnant recirculation at the inlet to the flushing channel. All training wall configurations were tested first in the 1:24 model while only the 25 ft wide versions were included in the 1:12 model. Tests included visual observations of flow patterns and sediment removal from the canal intake and apron. A bed scan of the adjacent riverbed upstream was made for the final configuration in the 1:24 model.

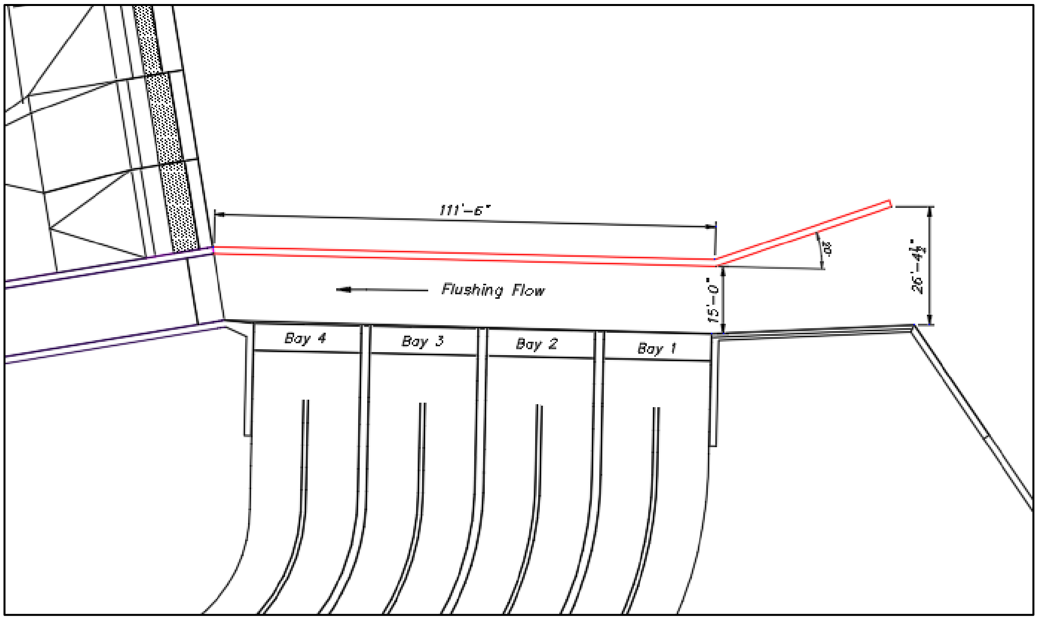


Figure 69. Layout of training wall parallel to the canal intake with a channel width of 15 ft.

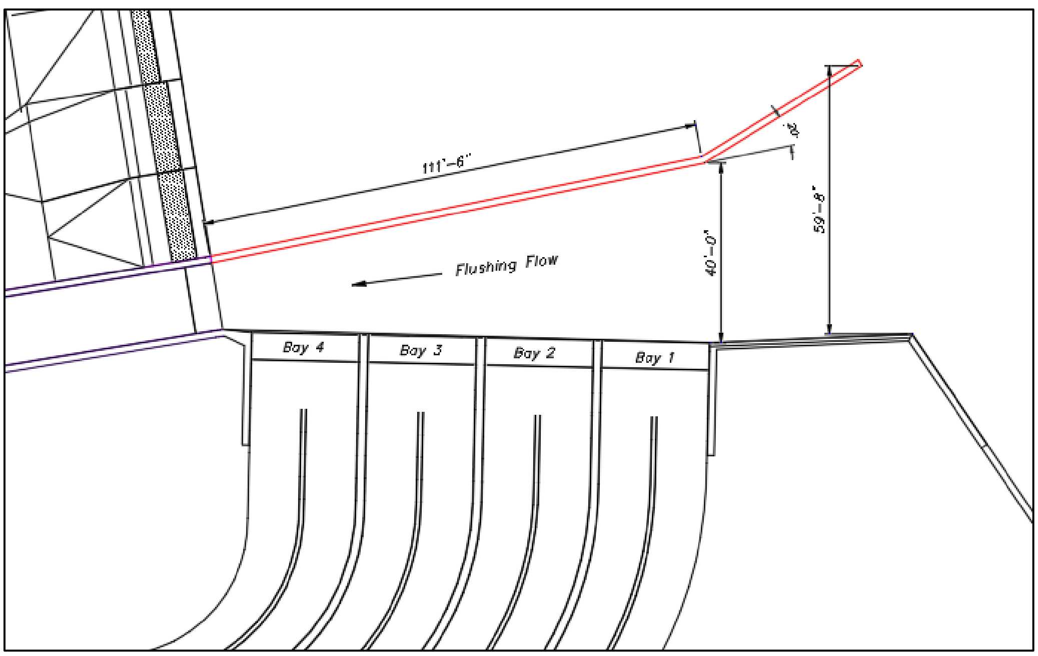


Figure 70. Layout of training wall with an upstream channel width of 40 ft.

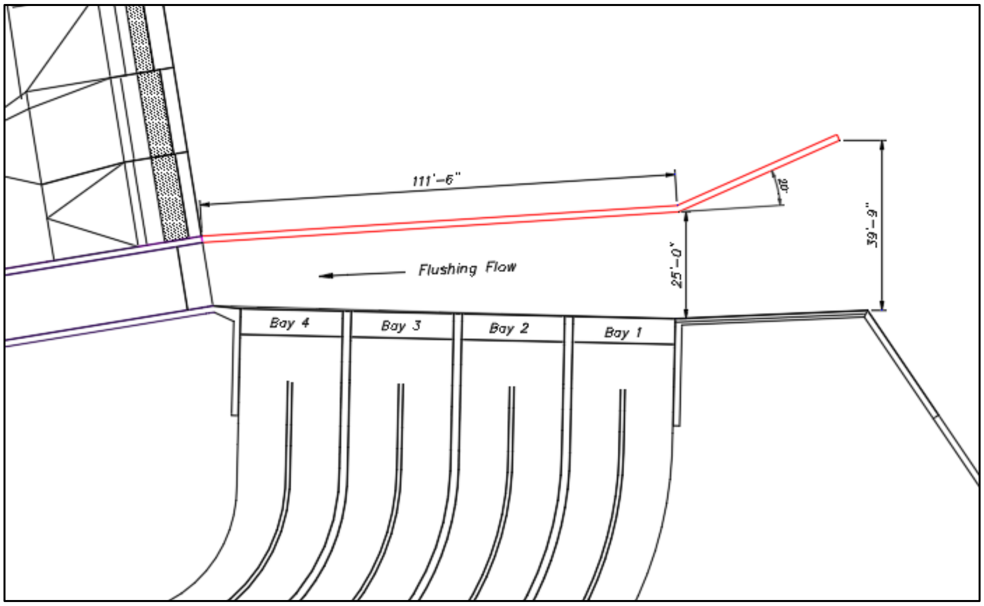


Figure 71. Layout of training wall with an upstream channel width of 25 ft.

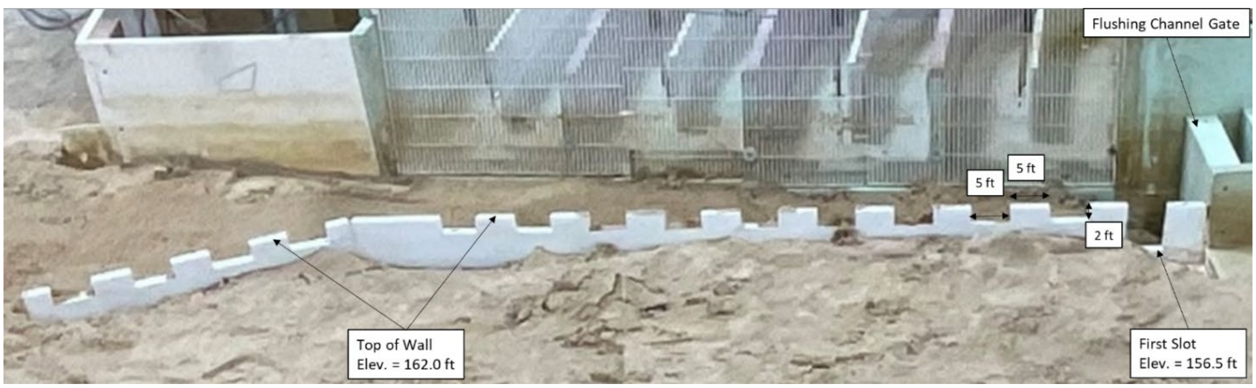


Figure 72. Photograph showing the castle training wall in the 1:24 model.

Normal Diverting Operations with a Flushing Channel – Test Results

Water level and discharge measurements for 6,000, 3,000, and 1,500 ft^3/s for the configuration with a flushing channel are shown in Table 18. There was no flow over the dam crest at 1,500 ft^3/s and there was a rather even flow split between the diversion and hardened ramp. Flow splits between the dam and hardened ramp at 3,000 ft^3/s and 6,000 ft^3/s appeared to be similar to tests without a flushing channel except that they were pushed further to the right due to sediment deposition along the right side of the ramp wall bullnose near the dam crest. This reduced the water surface elevation at the sensor near the right wall that was used for the rating curve to estimate flow over the dam which produced an inaccurate flow result (Table 18). Flow quantities over the dam were estimated to be similar to tests without a flushing channel. While patterns of scour and deposition were very similar to previous testing with the extended ramp wall bullnose, the quantity of sediment deposited near the dam along the right side of the ramp wall was greater than previous tests. This may have been due to differences in how much sediment was fed into the model by different lab personnel operating the model as described in the Shakedown Testing sections.

Table 18. Hydraulic results for the configuration with a castle training wall and flushing channel.

River Condition	Upstream Intake	Dam Crest	River Flow	Diversion Flow	*Dam Flow	*HR Flow
ft^3/s	*ft*	*ft*	*ft^3/s*			
6,000	163.8	162.2	6,106	842	411 *(1,500)	4,852 *(3764)
3,000	162.8	161.5	3,037	822	0 *(250)	2,264 *(1965)
1,500	-	-	1,539	805	0	734
** flow estimates from visual observations*						

Table 19 shows velocity and flow depth measurements at four gate locations across the hardened ramp fishway exit. Velocities were slightly higher and depths slightly lower compared to tests without a flushing channel. Turbulence and flow separation off the left ramp wall at gate 1 of the hardened ramp mostly cleared sediment similar to tests without a flushing channel. Sediment that deposited on the right side of the ramp exit pushed flow toward gates 1 through 3 particularly at 3,000 ft^3/s and 1,500 ft^3/s.

Table 19. Velocity and flow depth results from point measurements made at four hardened ramp upstream gate locations during testing with a castle training wall and flushing channel. Location 1 is on the left side of the hardened ramp fishway exit and location 4 is on the right side of the fishway exit.

River Flow	Hardened Ramp Location	Velocity	Flow Depth
ft^3/s	-	*ft/s*	*ft*
6,000	1	9.9	5.4
	2	9.0	4.2
	3	7.8	4.2
	4	6.2	4.0
3,000	1	4.0	5.6
	2	5.7	4.0
	3	6.0	3.2
	4	1.4	1.2
1,500	1	3.8	3.6
	2	1.4	0.8
	3	0.9	0.2
	4	DRY	DRY

Observations of flow patterns with dye, PIV results, photographs, and bedform contour maps of sediment patterns are shown in Figure 73 through Figure 87. These results include flows of 6,000, 3,000, and 1,500 ft^3/s. Results showed flow approaching the hardened ramp was more streamlined compared to baseline results. Flow streamlines were basically parallel with the hardened ramp walls across the full width at the upstream end of the ramp. A divergence of flow toward the canal intake began near the upstream end of the training wall and continued over and through the castle slots downstream splitting between the intake and hardened ramp. The gate of the flushing channel which had been moved up to the downstream end of the training wall prevented dead zones and recirculation near bay 4 of the canal intake.

A significant bed form developed in the area upstream of and on the hardened ramp exit and canal intake. Localized scour developed upstream of the bullnose on the hardened ramp right wall with deposition downstream toward the dam crest as previously noted. The castle training wall was mostly inundated with sediment at 6,000 ft^3/s but produced local scour on both sides of the wall from flow at lower water surface elevations as the flow receded to 3,000 ft^3/s and then 1,500 ft^3/s which reduced sediment elevations at each flow as seen in the photographs.

6,000 ft^3/s – Flushing Channel with Training Wall

Figure 73. Photograph of dye approaching the hardened ramp with a castle training wall and flushing channel at 6,000 ft^3/s.

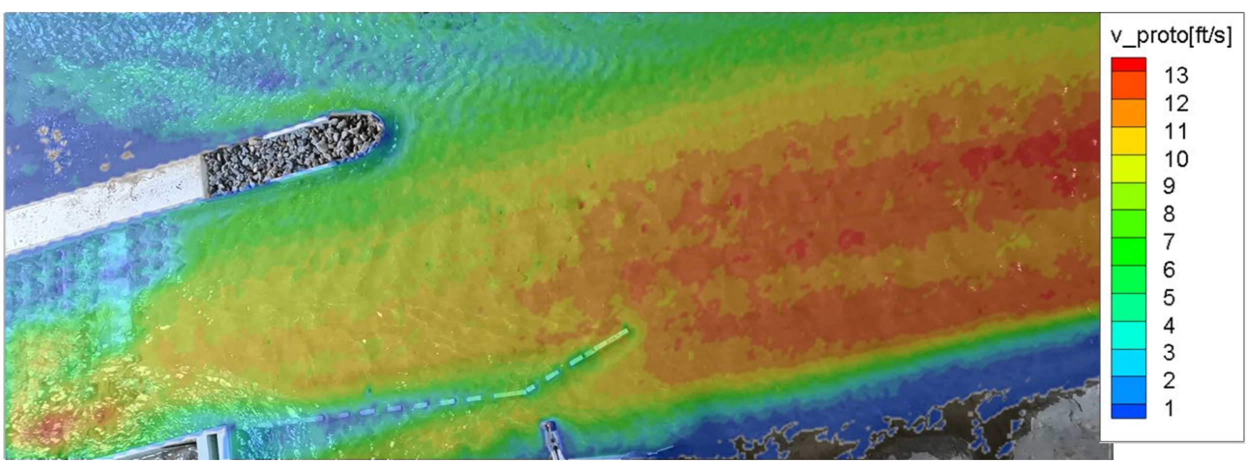


Figure 74. PIV contour plot of flow upstream of hardened ramp with a castle training wall and flushing channel at 6,000 ft^3/s.

Figure 75. Photographs of the sediment bedforms upstream of hardened ramp with a castle training wall and flushing channel at 6,000 ft^3/s.

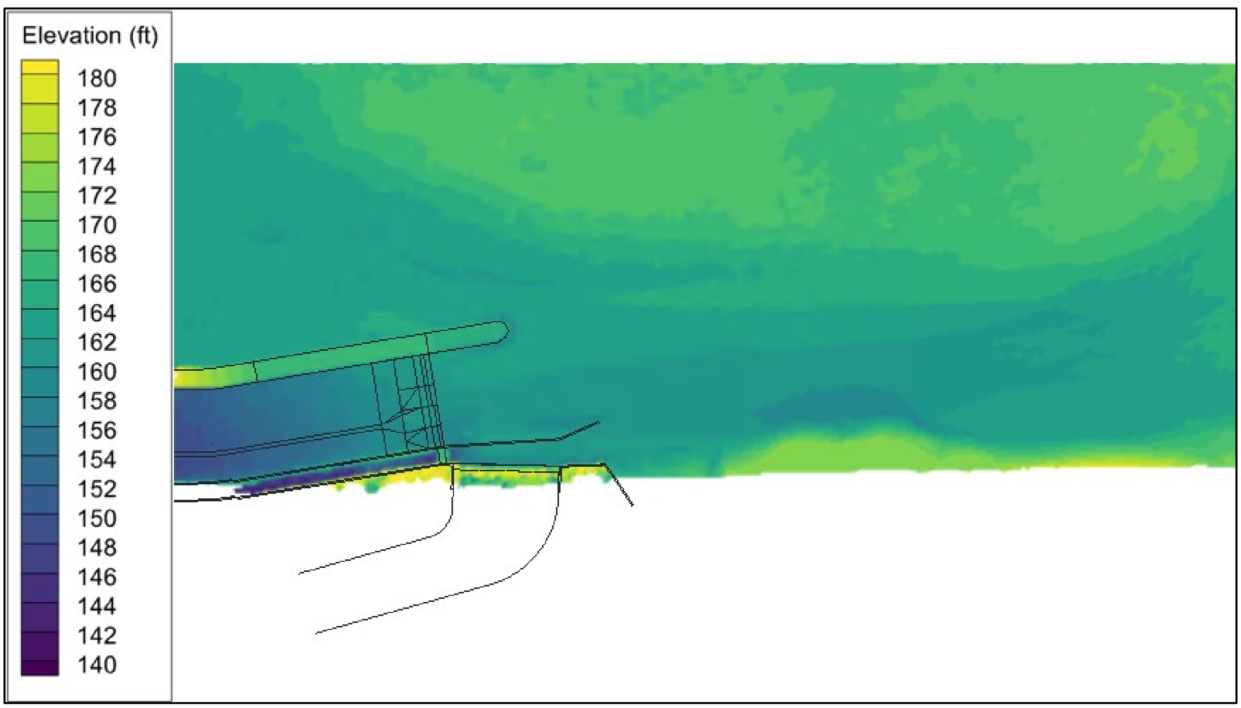


Figure 76. Color contour map of upstream bedform elevations with a castle training wall and flushing channel at 6,000 ft^3/s.

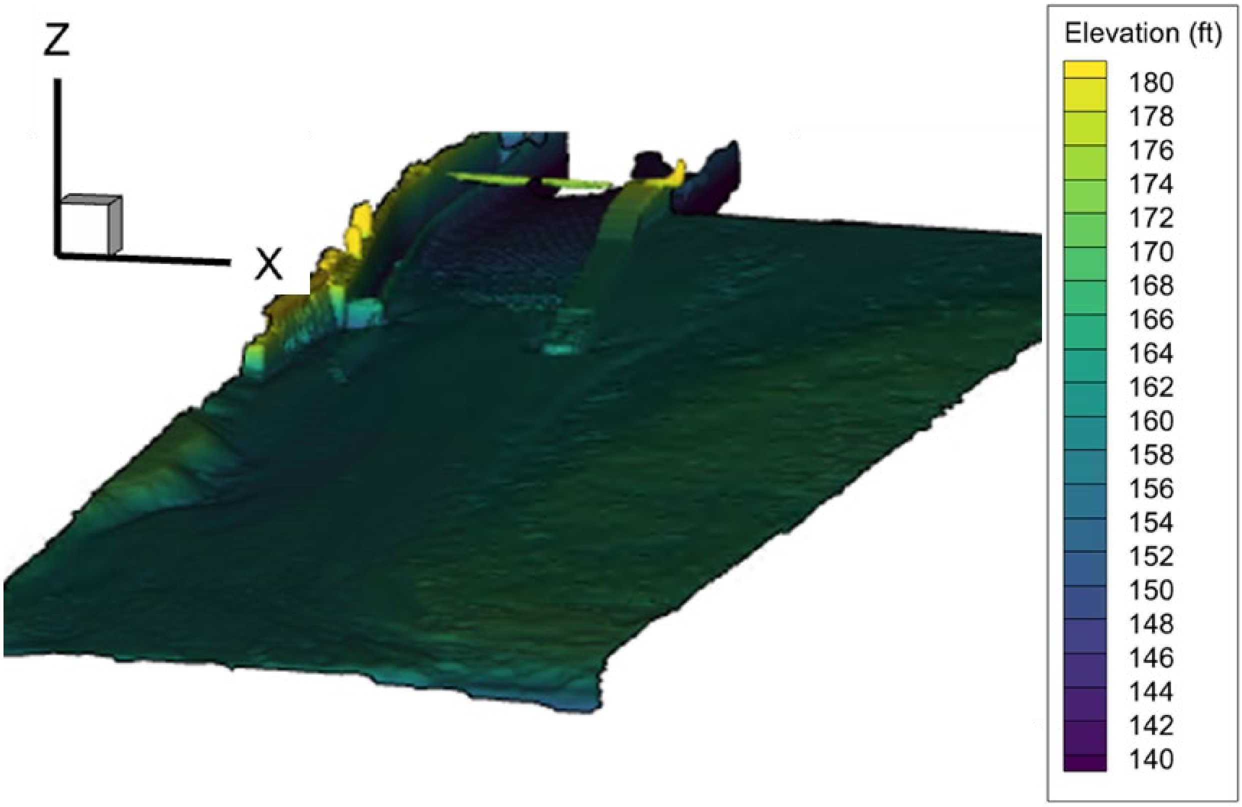


Figure 77. Isometric color contour map of upstream bedform elevations with a castle training wall and flushing channel at 6,000 ft^3/s. Looking downstream.

3,000 ft^3/s – Flushing Channel with Training Wall

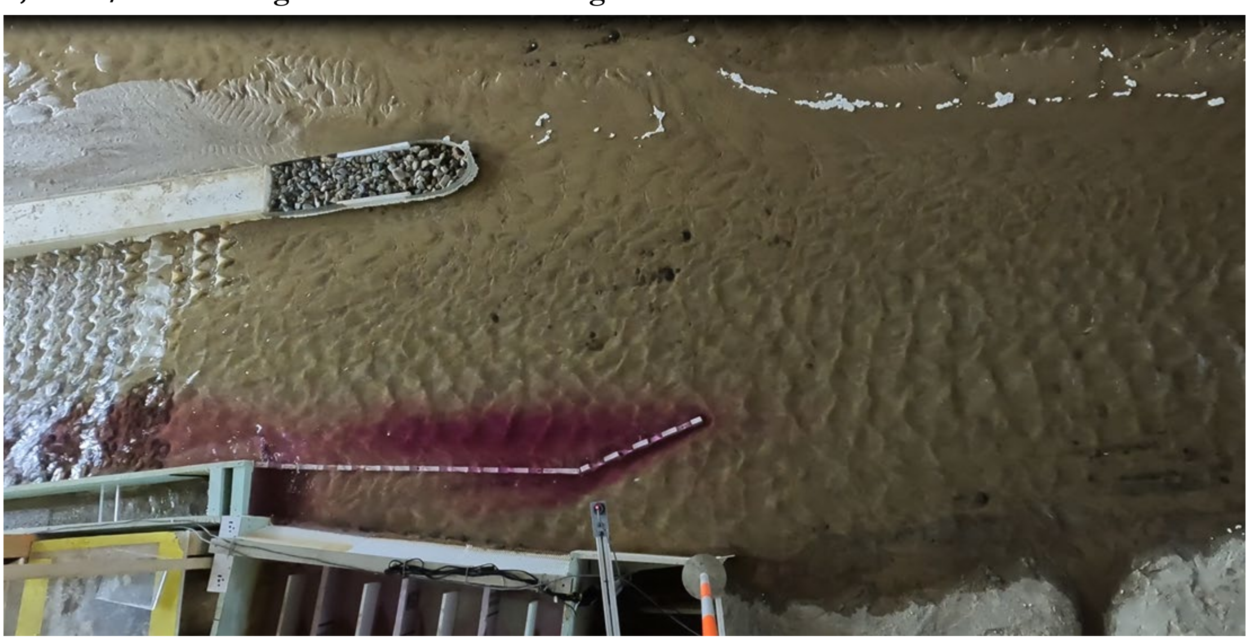


Figure 78. Photograph of dye approaching the hardened ramp with a castle training wall and flushing channel at 3,000 ft^3/s.

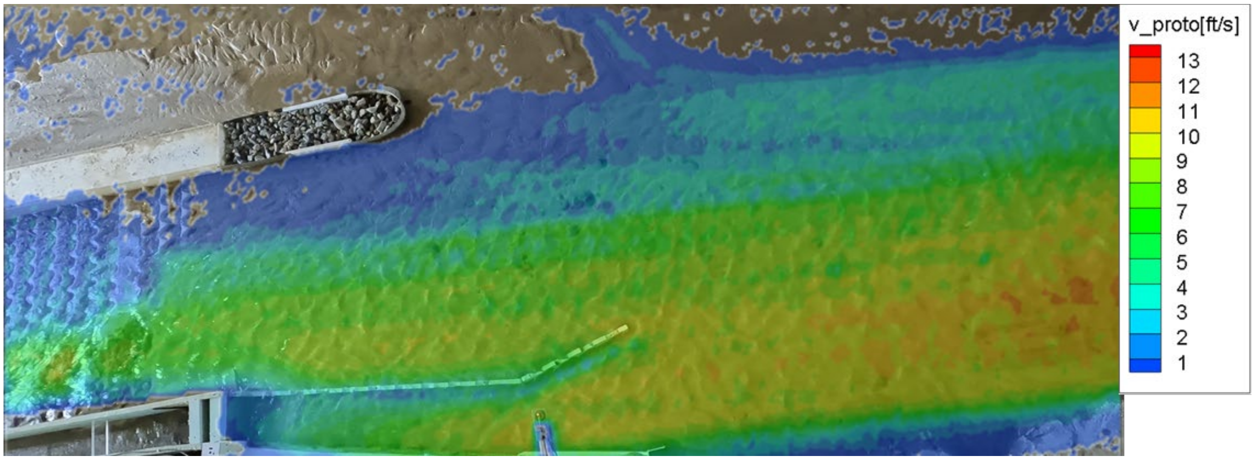


Figure 79. PIV contour plot of flow upstream of hardened ramp with a castle training wall and flushing channel at 3,000 ft^3/s.

Figure 80. Photographs of the sediment bedforms upstream of hardened ramp with a castle training wall and flushing channel at 3,000 ft^3/s.

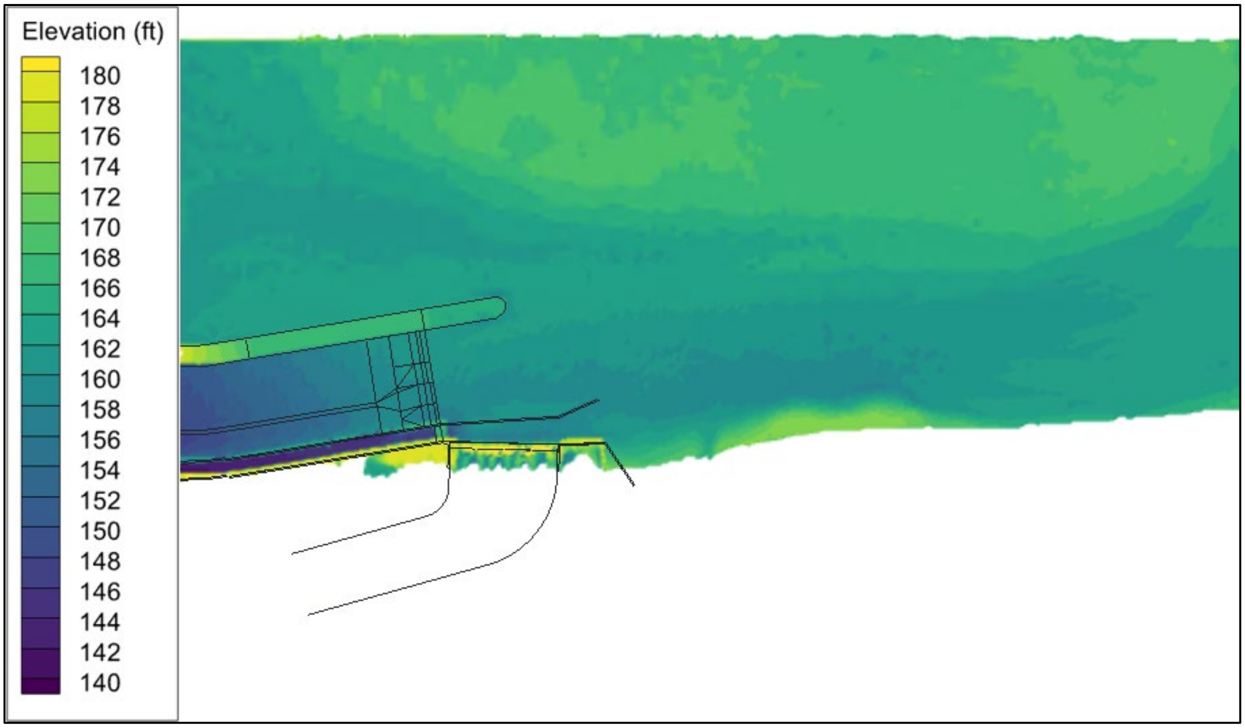


Figure 81. Color contour map of upstream bedform elevations with a castle training wall and flushing channel at 3,000 ft^3/s.

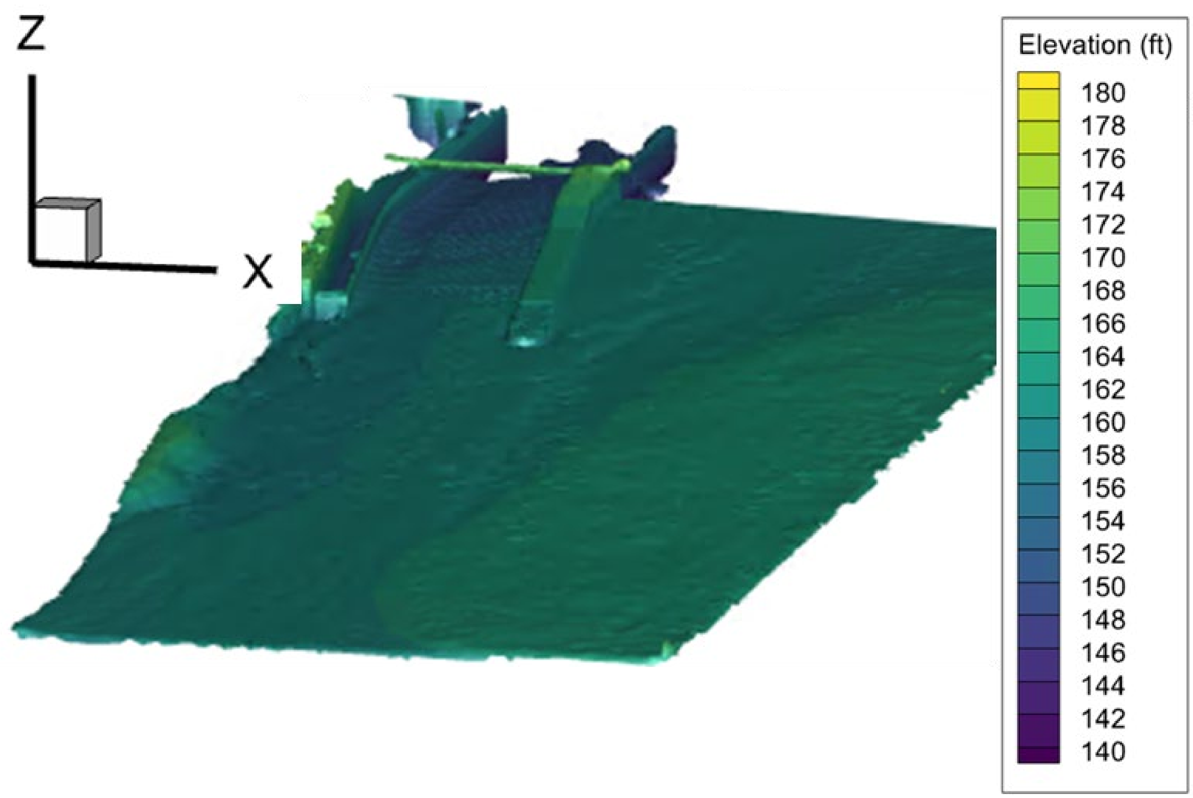


Figure 82. Isometric color contour map of upstream bedform elevations with a castle training wall and flushing channel at 3,000 ft^3/s. Looking downstream.

1,500 ft^3/s – Flushing Channel with Training Wall

Figure 83. Photograph of dye approaching the hardened ramp with a castle training wall and flushing channel at 1,500 ft^3/s.

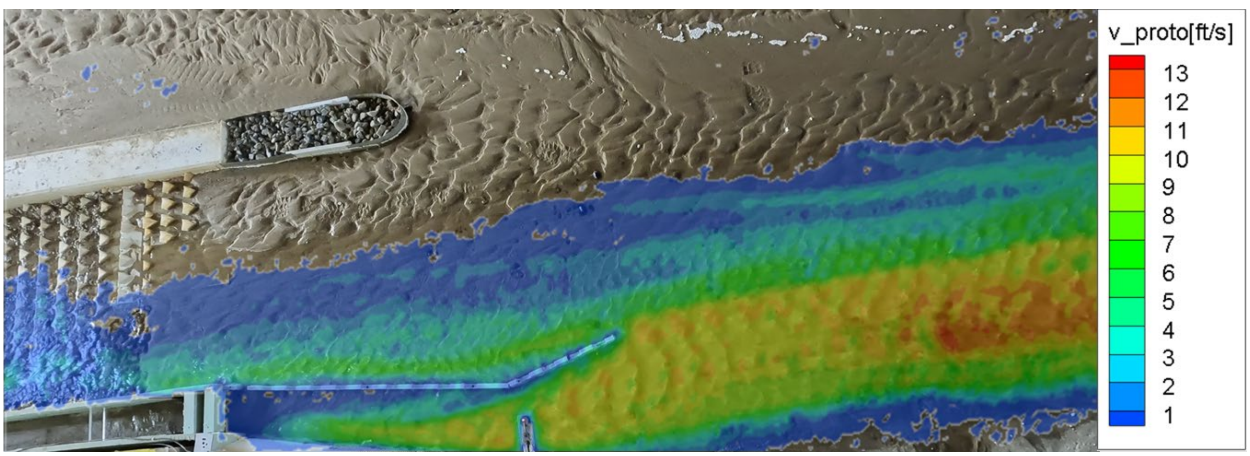


Figure 84. PIV contour plot of flow upstream of hardened ramp with a castle training wall and flushing channel at 1,500 ft^3/s.

Figure 85. Photographs of the sediment bedforms upstream of hardened ramp with a castle training wall and flushing channel at 1,500 ft^3/s.

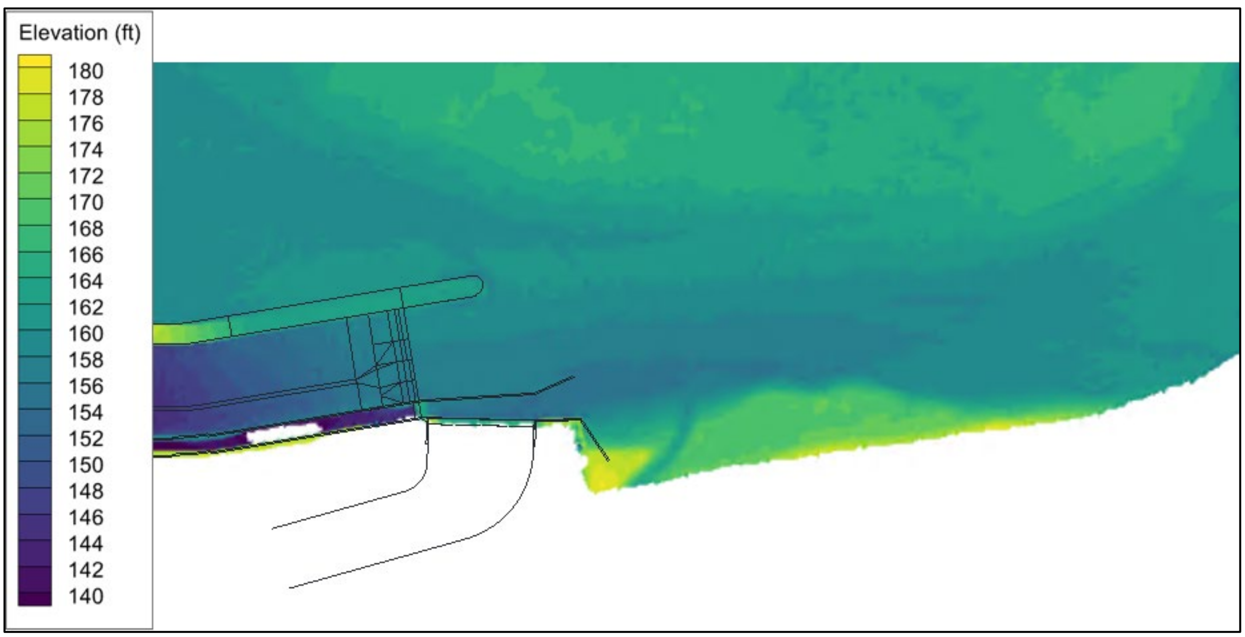


Figure 86. Color contour map of upstream bedform elevations with a castle training wall and flushing channel at 1,500 ft^3/s.

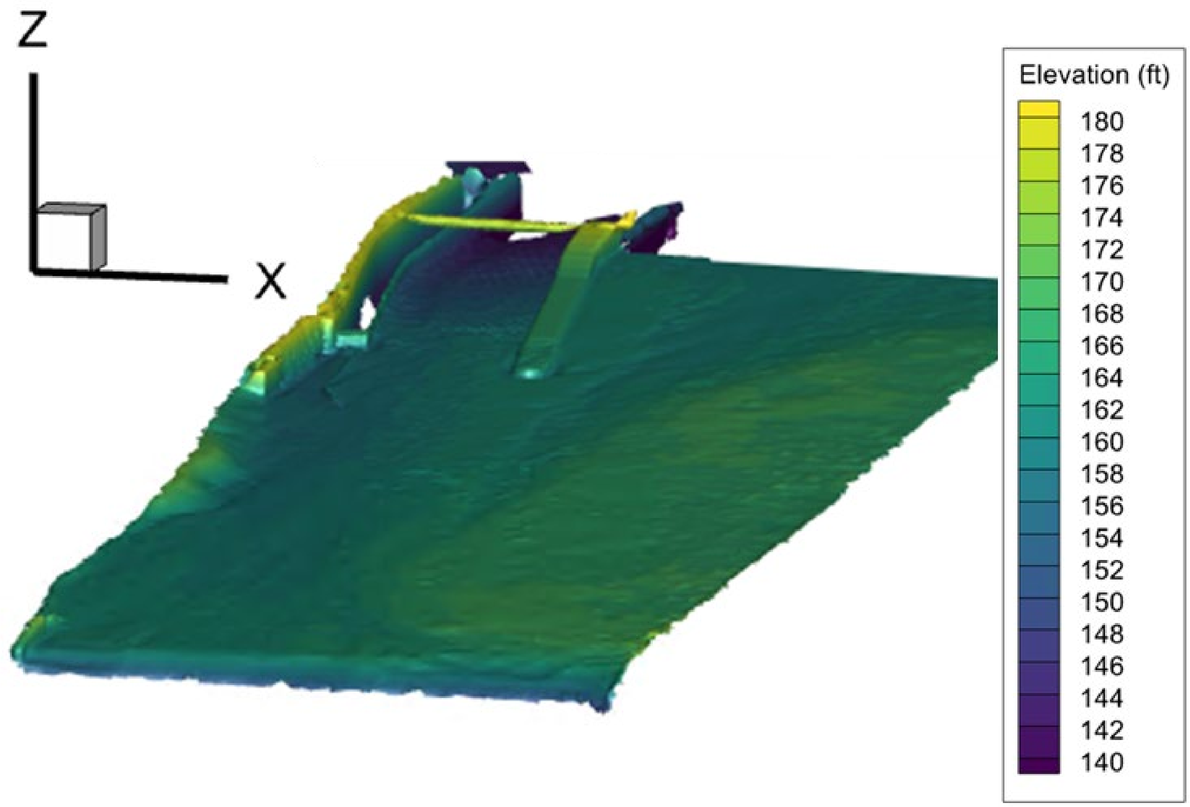


Figure 87. Isometric color contour map of upstream bedform elevations with a castle training wall and flushing channel at 1,500 ft^3/s. Looking downstream.

Flushing Operations – Test Results

Baseline tests showed that the original designs were ineffective at flushing deposited sediment away from the canal intake and gates. Several configurations of training walls were tested to improve flushing operations. Training wall configurations with top elevations below 160 ft were ineffective due to the inability to concentrate the flow on the apron sufficiently to remove the bedform. Configurations with a top wall elevation of 162 ft were the most effective without preventing diversion discharges from reaching their target.

The width of the upstream channel between the canal intake sill and training wall was also adjusted during testing. The training wall configuration with a 15-ft width was effective at concentrating flow and removing sediments but presented a possibility of reducing diversion flow due to its close proximity to the canal intake. The 40-ft wide configuration was unable to concentrate flow sufficiently to remove sediment. At 25-ft, in combination with a downward apron slope of 2.3%, sediments were easily moved into the flushing channel clearing the upstream apron between the intake and training wall. This design configuration was further enhanced by increasing the downward apron slope to 5.2% and added slots to the top of the training wall (castle) to help increase local turbulence and scour on both sides of the training wall.

The hardened ramp remained submerged during flushing operations at 3,000 ft^3/s and above as well as some flow over the dam crest (Figure 88). Flow remained in the low flow section of the hardened ramp but not within the baffled section for flushing operations at 1,500 ft^3/s. Flow splits for flushing tests were not measured.

Figure 88. Photographs of a flushing operation at 3,000 ft^3/s near the beginning of flushing (left) and midway through flushing (right). Looking downstream.

Flushing operations with the 5.2% downward slope and castle training wall effectively removed the sediment deposited upstream of the hardened ramp and canal intake. Figure 89 and Figure 90 show bedforms deposited upstream of the hardened ramp and intake following flows of 6,000 ft^3/s and 3,000 ft^3/s prior to flushing. The photograph and contour plots in Figure 91 through Figure 93 show that the bedform was removed following a flushing operation at 3,000 ft^3/s. The flushing operation was performed for 15 minutes on the model (on the order of 1.5 hrs prototype assuming Froude scaling) before the flushing channel gate was again closed and then the model shutdown and drained to observe the bed upstream. While the invert of the apron was not completely cleared from the flushing event, the floor was visible at many locations. Local scour along the right side of the training wall was observed along its entire length caused by turbulence of flow passing through the castle slots towards the flushing channel. Flushing also had an affect upstream where sediment was removed along the left bank for up to an additional 100 ft upstream of the training wall.

Figure 89. Photograph of bedform upstream of the hardened ramp and canal intake after 6,000 ft^3/s river flow and 825 ft^3/s diversion.

Figure 90. Photograph of bedform upstream of the hardened ramp and canal intake after 3,000 ft^3/s river flow and 825 ft^3/s diversion before flushing operations.

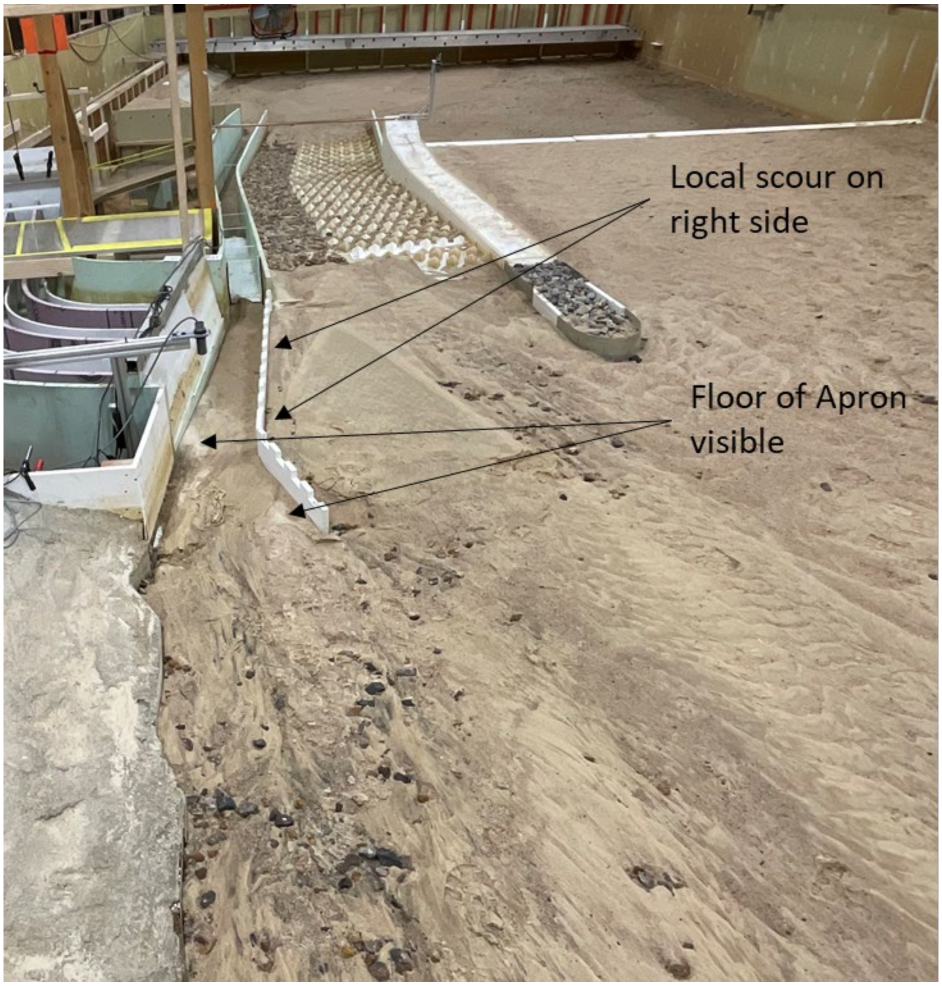


Figure 91. Photograph of bedform upstream of the hardened ramp and canal intake after a flushing operation at 3,000 ft^3/s.

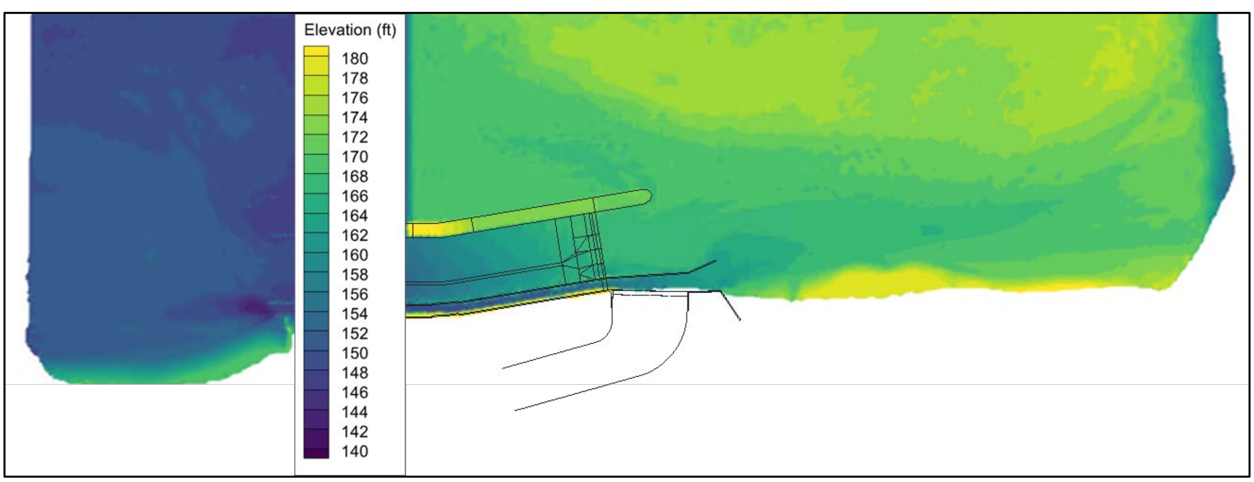


Figure 92. Color contour elevation plot after a flushing operation at 3,000 ft^3/s. Flow is to the left.

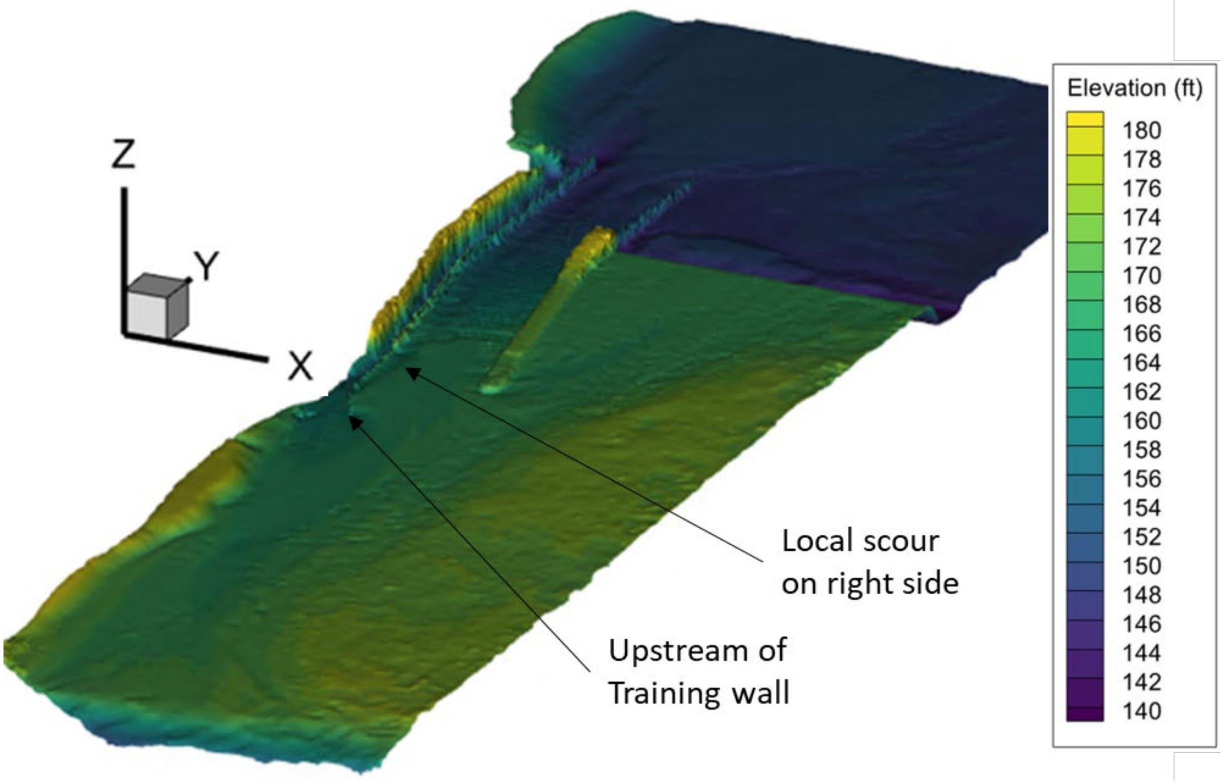


Figure 93. Isometric view of color contour elevation plot after a flushing operation at 3,000 ft^3/s. Looking downstream.

Downstream of the hardened ramp scour operations produced local scour near the outlet of the flushing channel and a plume of sediment distributed from the left bank across to the right side of the hardened ramp. These features are shown in the contour plots Figure 92 and Figure 93 as well as the photograph of Figure 94. A flow of 6,000 ft^3/s ran for 20 minutes in the model after the flushing operation and reformed the deposition downstream of the hardened ramp so that the flow stream lines became parallel to the left bank as was seen in previous runs (Figure 95).


Figure 94. Photograph of bedforms downstream of the hardened ramp following combined flushing and sediment sluicing operations. Looking upstream.

Figure 95. Photograph of flow streamlines on the downstream end of the hardened ramp at 6,000 ft^3/s following a flushing operation. Looking upstream.

Desander Sluicing System – Test Description

To help manage sediment at the canal intake, a "desander" sluicing system was developed by NHC and included in the 1:24 model. This system included four inner bay walls to isolate flow from each canal intake gate into independent channels within the canal intake upstream of the fish screens. Each channel or "bay" contained additional inner guide walls to direct the flow around the bend toward the fish screens and a lower-level outlet known as the sluicing culvert located beneath the canal and fish screens. During sluicing operations, a bottom gate to the lower sluicing culvert was opened to release sediment-laden flows back to the river via a sloped sluicing channel while a top gate was closed to prevent back flow of diversion water from the other bays into the sluicing bay. The design and operation of the desander are illustrated in Figure 96 through Figure 99.

Three versions of the desander system were tested and their respective elevations, slopes and dimensions are shown in Table 20. Concept testing of Version 1 included only the desander portion (wall sections within the canal intake) and compared configurations of the inner guide walls to help determine spacing and number of guide walls needed for effective sluicing as well as favorable hydraulic conditions for entrained fish. These included dual guide walls, a single guide wall, and no guide walls (bay walls only) shown in Figure 96. Versions 2 and 3 included the addition of the sluicing culvert and channel (made of transparent plexiglass). The slope and opening (culvert height) was increased in Version 3 to 5 ft, the slope increased to 3%, and the inner piers from the bay walls were extended. Also, the outlet of the sluiceway channel was combined with the flushing channel for a single outlet at elevation 134.0 ft.

The desander was not tested in the 1:12 model due to space limitations in the laboratory.

Table 20. Elevations and slopes of the three configurations (versions) of the desander and sluiceway system tested in the 1:24 physical model.

Desander Version 1 Geometry						
Bay	***Sill Elevation***	***Invert Upstream Elevation***	***Invert Downstream Elevation***	***Culvert Height***	***Desander Slope***	***Sluiceway Slope***
1	156.5	155.5	148.0	3.0	2.30%	Not Tested
2	156.5	155.5			2.60%	
3	156.5	155.5			2.90%	
4	156.5	155.5			3.30%	
Desander Version 2 Geometry						
Bay	***Sill Elevation***	***Invert Upstream Elevation***	***Invert Downstream Elevation***	***Culvert Height***	***Desander Slope***	***Sluiceway Slope***
1	156.5	155.5	148.0	3.0	2.57%	1.6%
2	156.5	155.5			2.84%	
3	156.5	155.5			3.17%	
4	154.0	153.0			2.87%	
Desander Version 3 Geometry						
Bay	***Sill Elevation***	***Invert Upstream Elevation***	***Invert Downstream Elevation***	***Culvert Height***	***Desander Slope***	***Sluiceway Slope***
1	156.5	155.5	146.0	5.0	3.25%	3.0%
2	156.5	155.5			3.59%	
3	154.0	153.0			3.38%	
4	154.0	153.0			3.82%	

Testing of Version 1 was only performed on bays 1 and 4 as they represented the extremes in slopes. Changes to the guide walls were only made in these bays as shown in Figure 96 included making them higher to prevent sediment overtopping among the guide walls and to concentrate flow. Bays 2 and 3 were not tested nor modified during testing of Version 1.

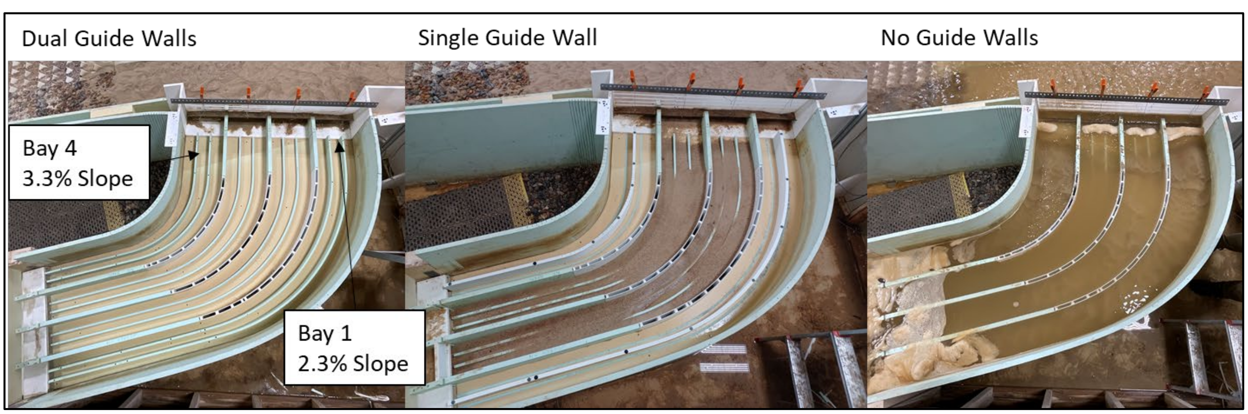


Figure 96. Photographs comparing the inner guide wall configurations for Version 1 of the desander for concept testing. Testing and modifications of the inner guide walls were only made in bays 1 and 4.

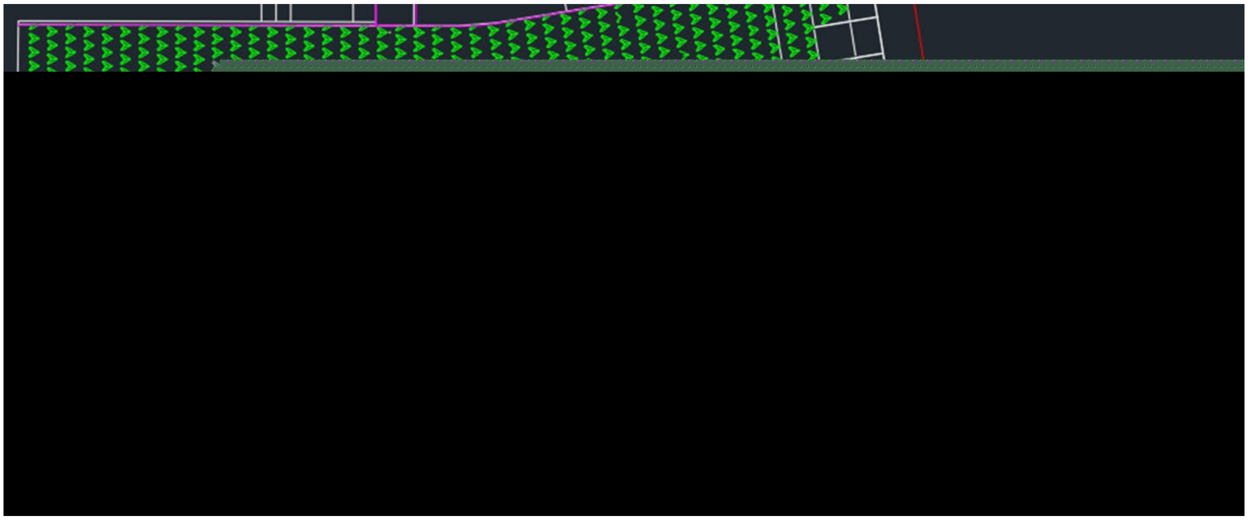


Figure 97. Layout of the desander (red) and comparing the plan view of Version 2 sluiceway (green) to the Version 3 sluiceway (white lines that tie into the outlet of the flushing channel).

Figure 98. Photograph of downstream end of the Version 3 desander, top and bottom control gates, and sluiceway (clear acrylic), looking downstream.

Figure 99. Photograph showing the Version 3 sluiceway channel (clear acrylic) tied into the outlet of the Version 3 flushing channel (looking upstream).

Desander Sluicing System – test results

Desander Version 1 (concept test)

Test results of the first version of the desander concept compared the efficacy of sluicing sediments within the canal intake with different guide wall configurations. Resulting rates of sediment sluicing by volume are shown in Table 21. Visual observations (Figure 100 through Figure 105) showed that desander bays without internal guide walls were ineffective and that there were minor differences between one or two guide walls for each independent bay. Due to Version 1 test results, Versions 2 and 3 of the desander system included a single inner guide wall for each bay.

Table 21. Sediment sluicing comparisons of the guide wall configurations testing in Version 1 of the desander. Times and volumes represent prototype-scale values.

Configuration	Bay	Invert Slope	Time to sluice	Sediment Volume	Approximate Sluicing Rate
-	-	-	*minutes-prototype**	*yd^3*	*yd^3/min*
No Guide Walls	Bay 1	2.30%	152		*n/a - stopped test*
	Bay 4	3.34%	69		*n/a - stopped test*
Dual Guide Walls	Bay 1	2.30%	103	550	5.3
	Bay 4	3.34%	32	325	10.2
Single Guide Walls	Bay 1	2.30%	122	700	5.7
	Bay 4	3.34%	38	400	10.5
** Froude scaling of duration may be different for sediment transport*					

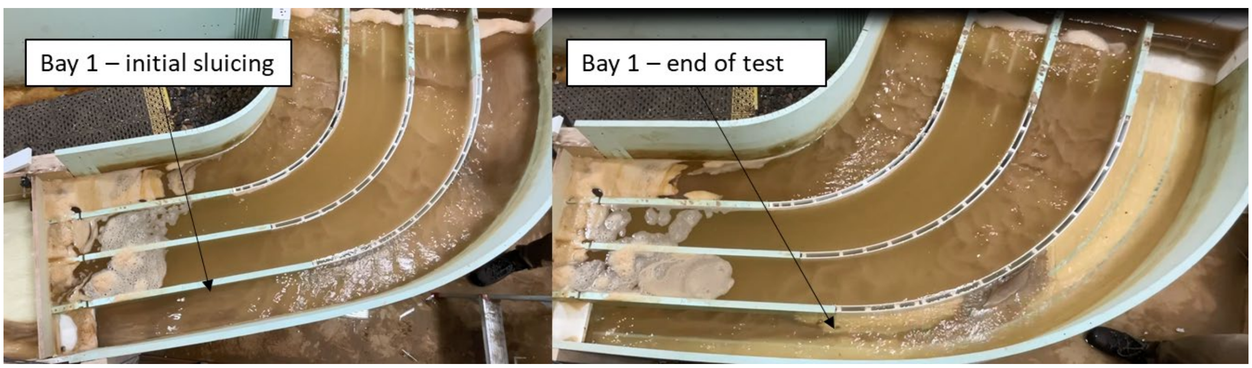


Figure 100. Photographs showing sluicing flows in Bay 1 without guide walls.

Figure 101. Photographs showing sluicing flows in Bay 4 without guide walls.

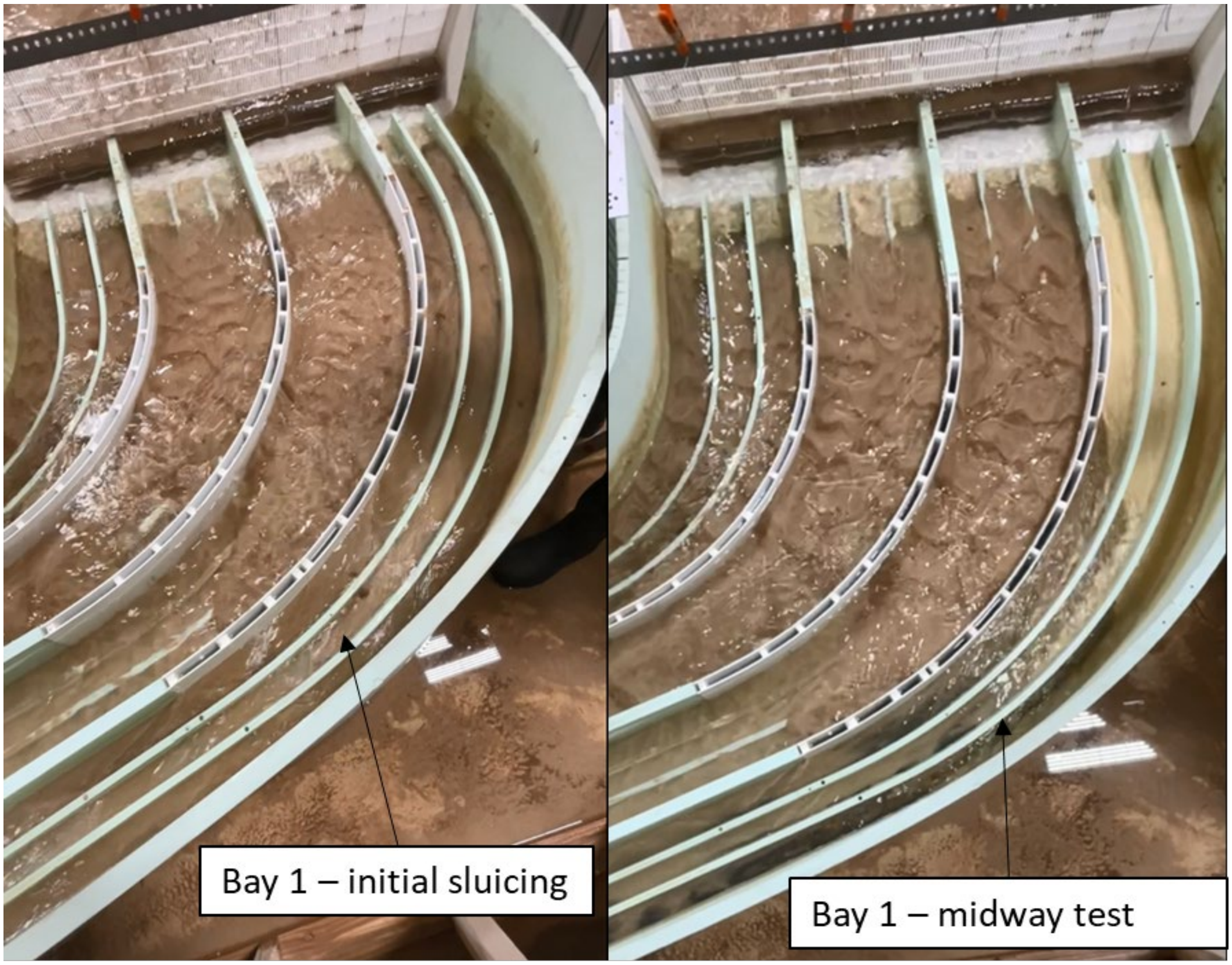


Figure 102. Photographs showing sluicing flows in Bay 1 with dual guide walls.

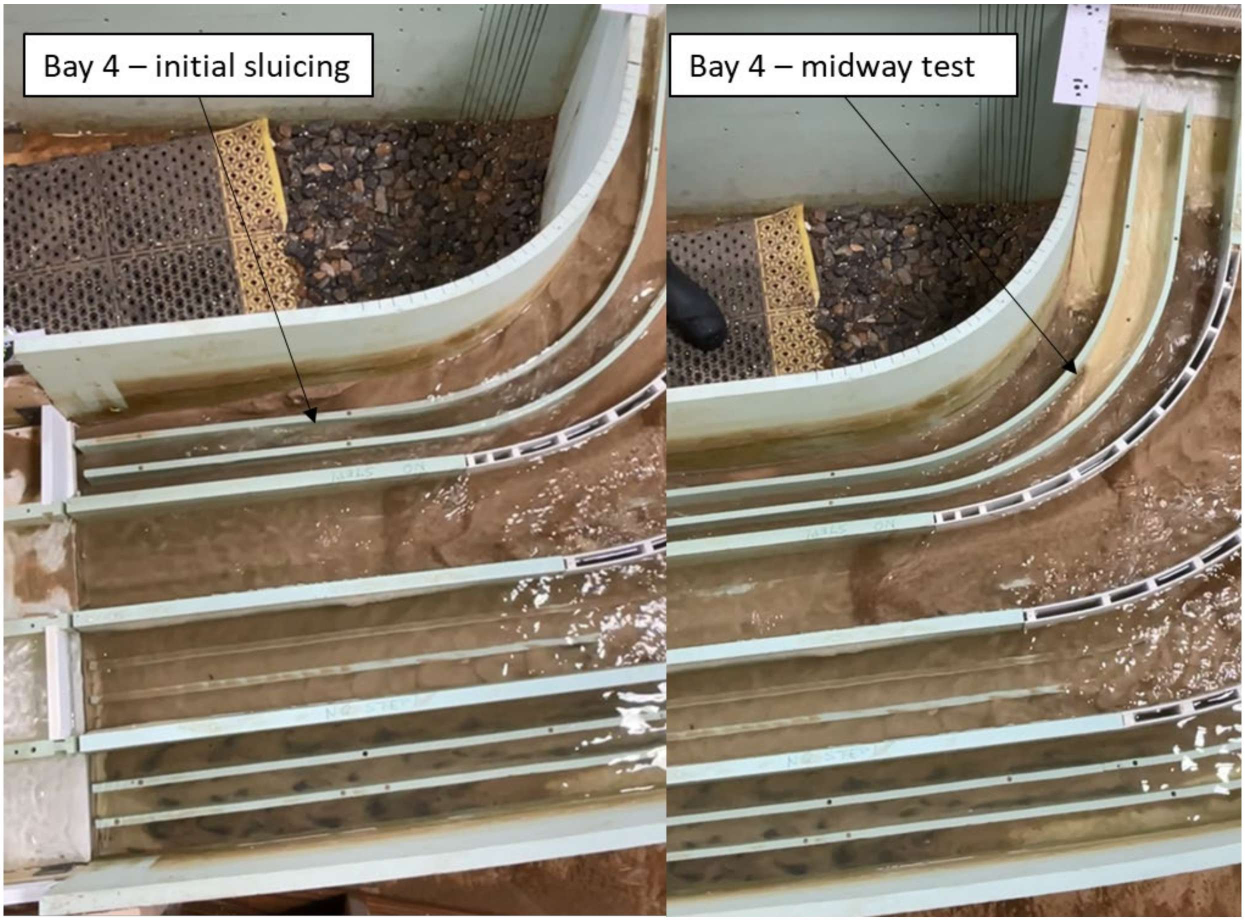


Figure 103. Photographs showing sluicing flows in Bay 4 with dual guide walls.

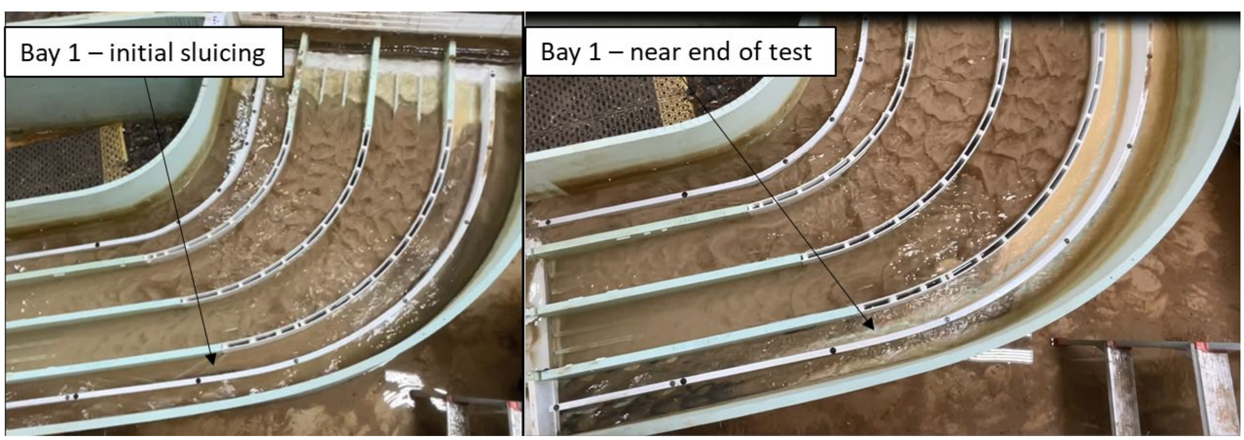


Figure 104. Photographs showing sluicing flows in Bay 1 with a single guide wall.

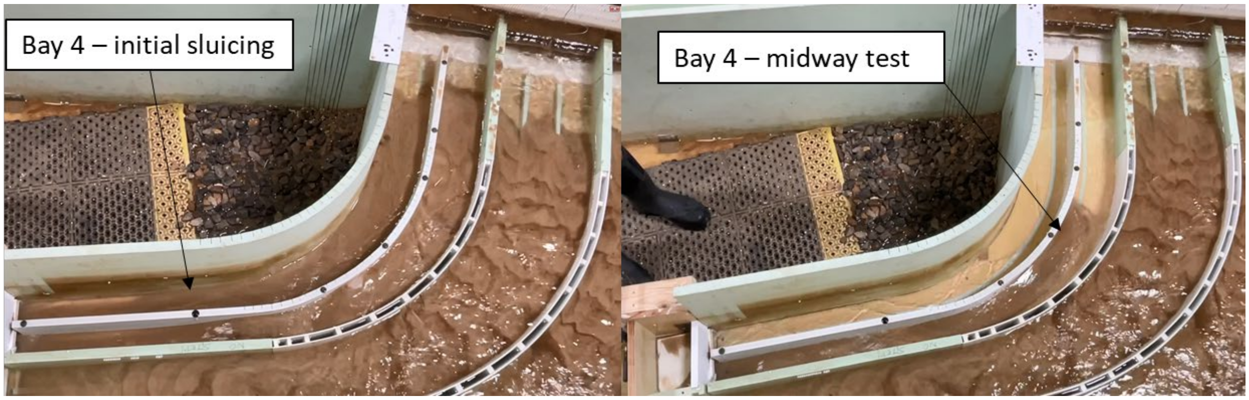


Figure 105. Photographs showing sluicing flows in Bay 4 with a single guide wall.

Desander Version 2

Testing for the second version of the desander focused on the sluicing culvert and channel downstream of the desander and only included visual observations of hydraulic and sediment transport conditions. Testing showed that the volume of clear water at the downstream end of the desander (immediately upstream of the entrance to the sluicing culvert where sediment had not yet accumulated) was drained within only a few seconds after the lower sluice gate was opened, providing an initial volume of clear water through the system before passing sediment laden flow. Flow in the desander and throughout the sluicing culvert and channel soon stabilized in an open channel supercritical flow condition.

Figure 106 is a schematic describing flow conditions within the sluicing culvert. Flow from each bay discharged from the desander and was turned to the right and downstream by the inner pier walls. Some of the flow however was directed into the left wall of the culvert, causing flow separation, recirculation, and turbulence. These conditions produced areas of sediment deposition on both sides of each bay within the culvert (Figure 107). Accumulation of sediment within the culvert caused a backwater effect on incoming flow that pressurized within the culvert and produced a hydraulic jump in the desander bay upstream. This occurred until sediment within the culvert was cleared away sufficiently for the hydraulic jump to retreat downstream and then return to open channel flow. This oscillation between pressurized and open channel flow continued over time as sediment accumulated and cleared away and was consistent for each bay. These observations prompted further design changes to the geometry of the sluicing culvert for Version 3 including increasing the inlet opening height to 5 ft, increasing the slope to leading to 3%, and extending the inner pier wall curvature 8, 10, and 12 ft.

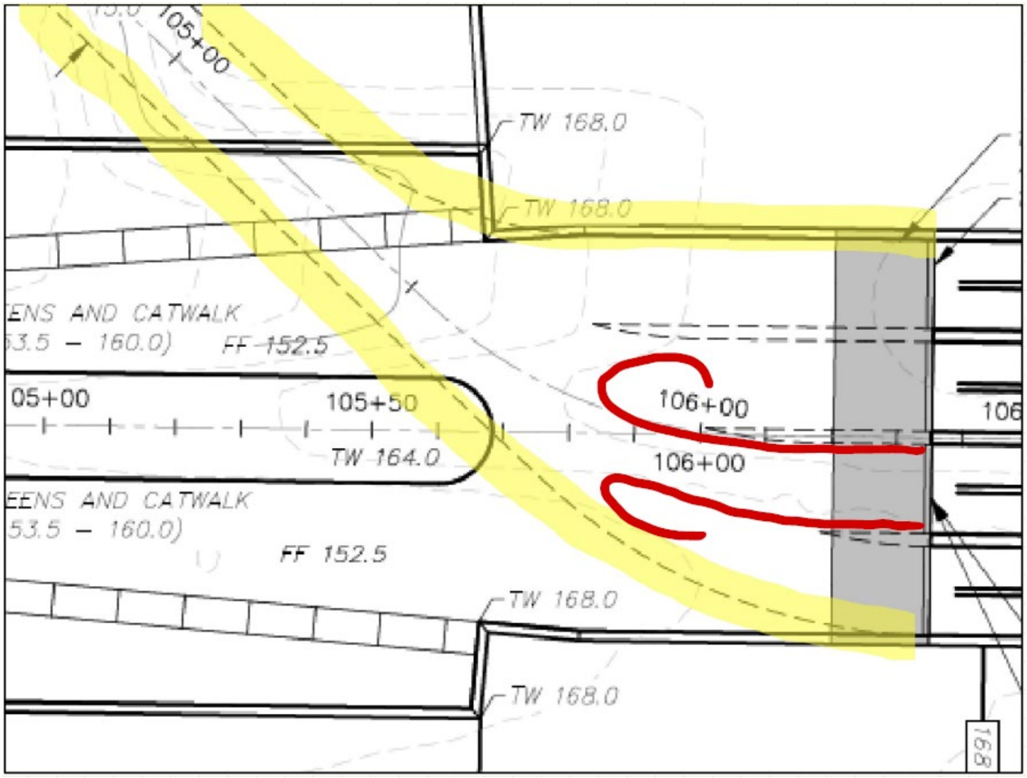


Figure 106. Schematic illustrating unfavorable flow conditions that were observed exiting the desander gates within the sluicing culvert.

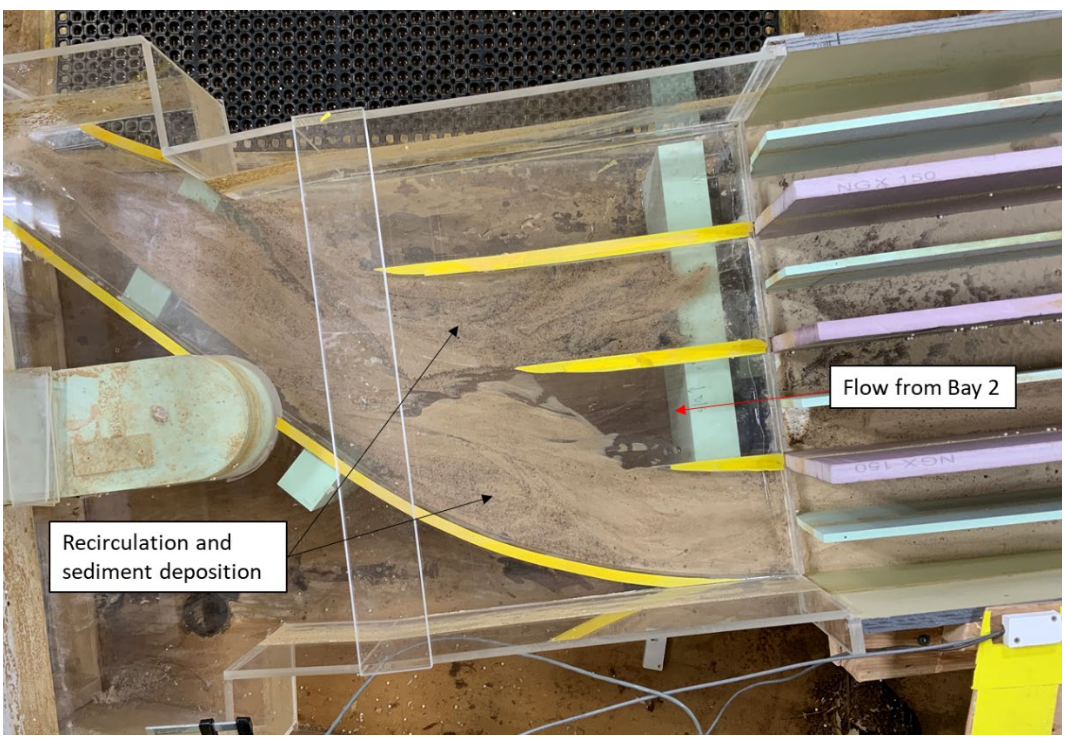


Figure 107. Photograph showing sediment deposition patterns within the Version 2 sluicing culvert.

Desander Version 3

Visual observations within the Version 3 sluicing culvert demonstrated that the flow conditions were improved compared to Version 2. Photographs of dye flow patterns in Figure 108 through Figure 111 show flow exiting the desander and passing through the culvert for each bay. The updated geometry of Version 3 helped turn the flow to the right downstream with reduced impact to the left wall and minimal flow separation and recirculation.

Approximate sediment sluicing rates were measured for each of the four bays shown in Table 22. Results are similar to those produced for Version 1. However, the rate of bay 1 was approximately twice that of bays 3 and 4 which may have been due to sluicing in that sequential order. Sediment from bays 1 and 2 accumulated in the downstream end of the culvert and channel causing the downstream water surface at the sluicing outlet to rise from 143.9 ft to just under 146 ft during sluicing of bays 3 and 4 reducing their efficacy at removing sediment. Average tail water elevations downstream of the dam remained close to 143 ft during all sluicing operations. Testing of the reverse sequential order from bay 4 to bay 1 was not performed.

Figure 108. Photographs showing flow patterns with dye exiting the outside (left) and inside (right) channels of Bay 1. Sluicing flow was approximately 200 ft^3/s.

Figure 109. Photographs showing flow patterns with dye exiting the outside (left) and inside (right) channels of Bay 2. Sluicing flow was approximately 200 ft^3/s.

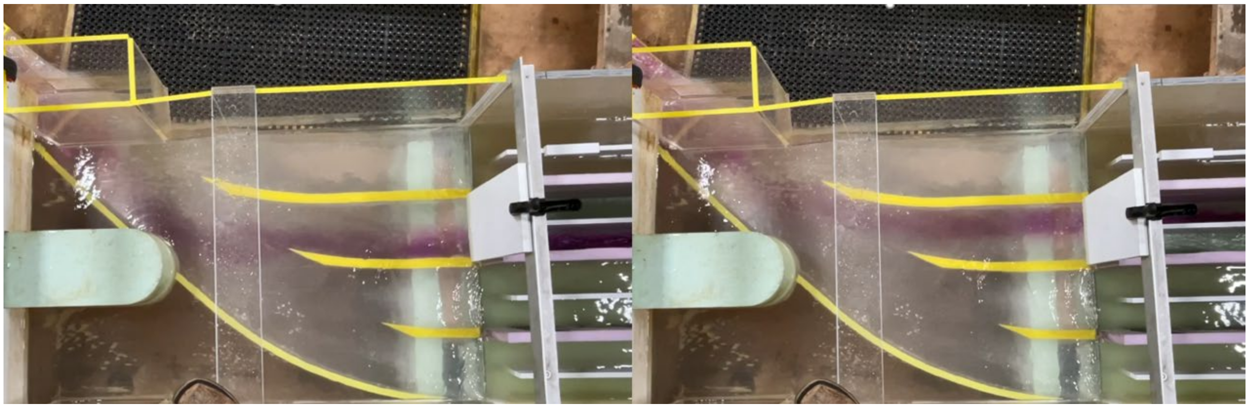


Figure 110. Photographs showing flow patterns with dye exiting the outside (left) and inside (right) channels of Bay 3. Sluicing flow was approximately 200 ft^3/s.

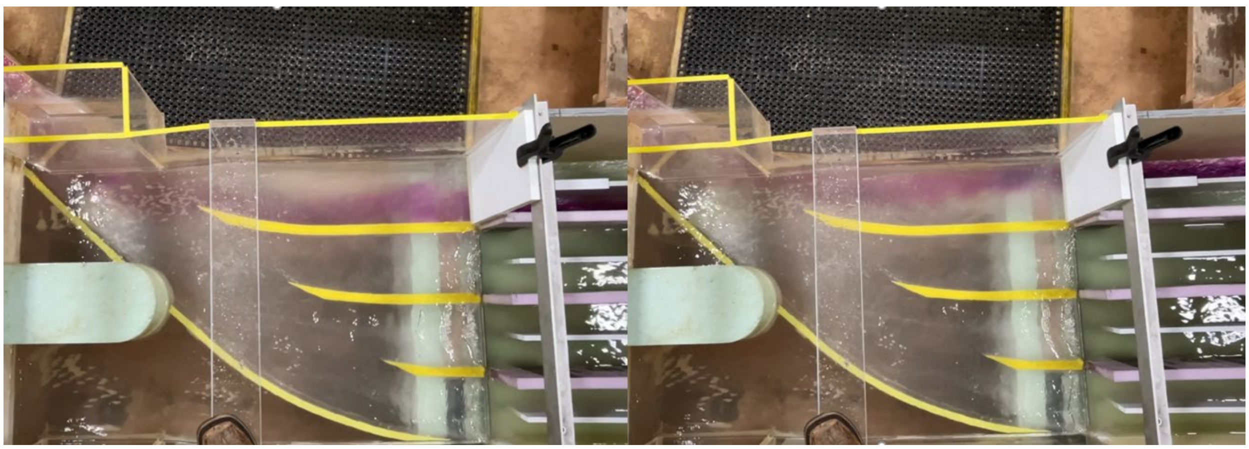


Figure 111. Photographs showing flow patterns with dye exiting the outside (left) and inside (right) channels of Bay 4. Sluicing flow was approximately 200 ft^3/s.

Table 22. Sediment sluicing comparisons of the guide wall configurations tested in Version 3 of the desander. Times and volumes represent prototype values.

Bay	Invert Slope	Time to Sluice	Sediment Volume	Approximate Sluicing Rate	Channel Outlet WSE
-	-	*minutes - prototype**	*yd^3*	*yd^3/min*	*ft*
1	3.82%	34	374	10.9	143.9
2	3.38%	64	453	7.1	145.0
3	3.59%	108	453	4.2	145.9
4	3.25%	44	227	5.1	145.8
** Froude scaling of duration may be different for sediment transport*					

Additional testing for Version 3 focused on the effects of downstream tailwater on transport of sediments through the culvert and downstream sluiceway channel. These tests were conducted at a river flow of 3,000 ft^3/s with varying tail water elevations. Tests at a tailwater elevation of 145 ft produced a hydraulic jump within the sluicing culvert near the downstream end of the pier wall extensions that reduced sediment transport rates and formed sediment deposits within the culvert and downstream channel (Figure 112). This occurred at flow rates of approximately 200 ft^3/s through each desander bay. Intake gate positions were not changed during this sluicing test, and bays were switched as soon as the upstream desander was cleared of sediment, not giving additional sluicing time with clear water to help remove sediment within the culvert. Sediment depths in the downstream sluicing channel varied from 1 to 4 ft. The accumulation of sediment deposits downstream caused the water level within the sluiceway channel to increase to between 146 and 148 ft in elevation locally, even though the average tailwater in the river channel downstream remained at 145 ft. Water levels at this location oscillated within this range as the bedforms within the channel were cleared away and then reformed.

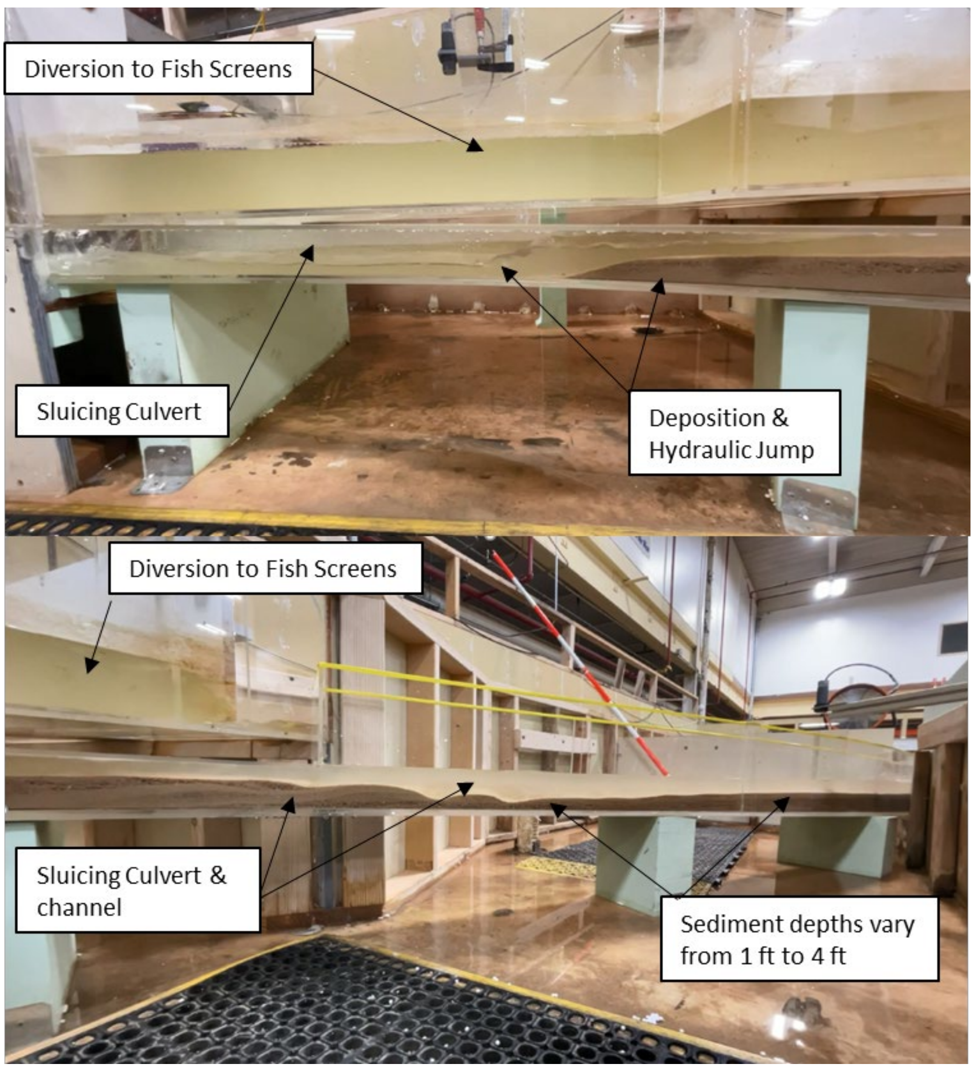


Figure 112. Photographs showing water surface and sediment deposition profiles withing the sluicing culvert (top) and the downstream sluicing channel (bottom) at a tailwater elevation of 145 ft. Water is flowing left-to-right.

For the same unmodulated flow conditions within the desander (steady state flow of approximately 200 ft^3/s each bay), similar results and observations were made for a tailwater elevation of 147.5 ft. At this condition the hydraulic jump moved further upstream into the desander, further reducing sediment transport rates and increasing sediment deposition within the culvert and downstream sluiceway channel (Figure 113).

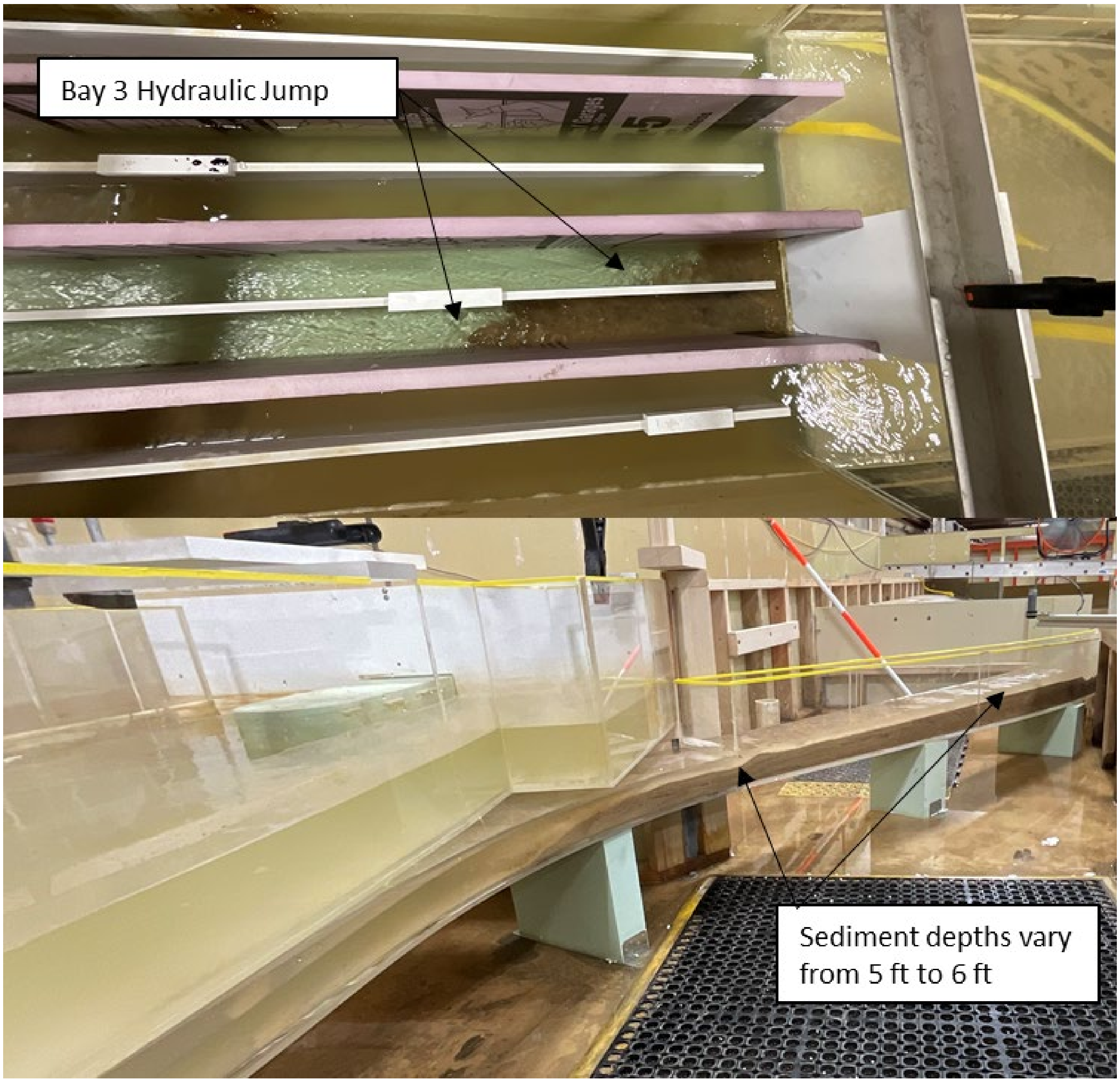


Figure 113. Photographs showing hydraulic jump and reduced sluicing efficacy in Bay 3 (top) and sediment deposition in the downstream sluicing channel (bottom) at a tailwater elevation of 147.5 ft. Water is flowing from left to right.

With significant sediment deposits within the culvert and sluice channel as an initial condition (remaining from tests at tailwater of 147.5 ft), a test was conducted to determine if the sediment could be removed from the desander and sluice system by modulating the flow through each bay with the canal intake gates. This test was performed with a tailwater elevation of 145 ft. After performing a flushing operation to ensure clear water was coming into the intake, sluicing operations were repeated beginning with bay 1 at a higher discharge and then rotating through the other bays. Unmodulated flows through each bay were not measured but were estimated to be between 300 and 400 ft^3/s each, based on differences from measured diversion flows and canal intake gate elevations. Rotating sluicing operations at the four desander bays with clear water (incoming sediment eliminated by flushing operation) helped remove sediment within the desander and eventually transport sediment bedforms within the sluicing channel back to the downstream river (Figure 114 and Figure 115), completely removing sediment from the sluicing culvert and downstream channel.

Also, observations showed that operating two bays (approximately 200 ft^3/s each) simultaneously helped expedite clearing of sediment accumulated within the culvert and downstream channel. More detailed tests to optimize desander operations were not performed.

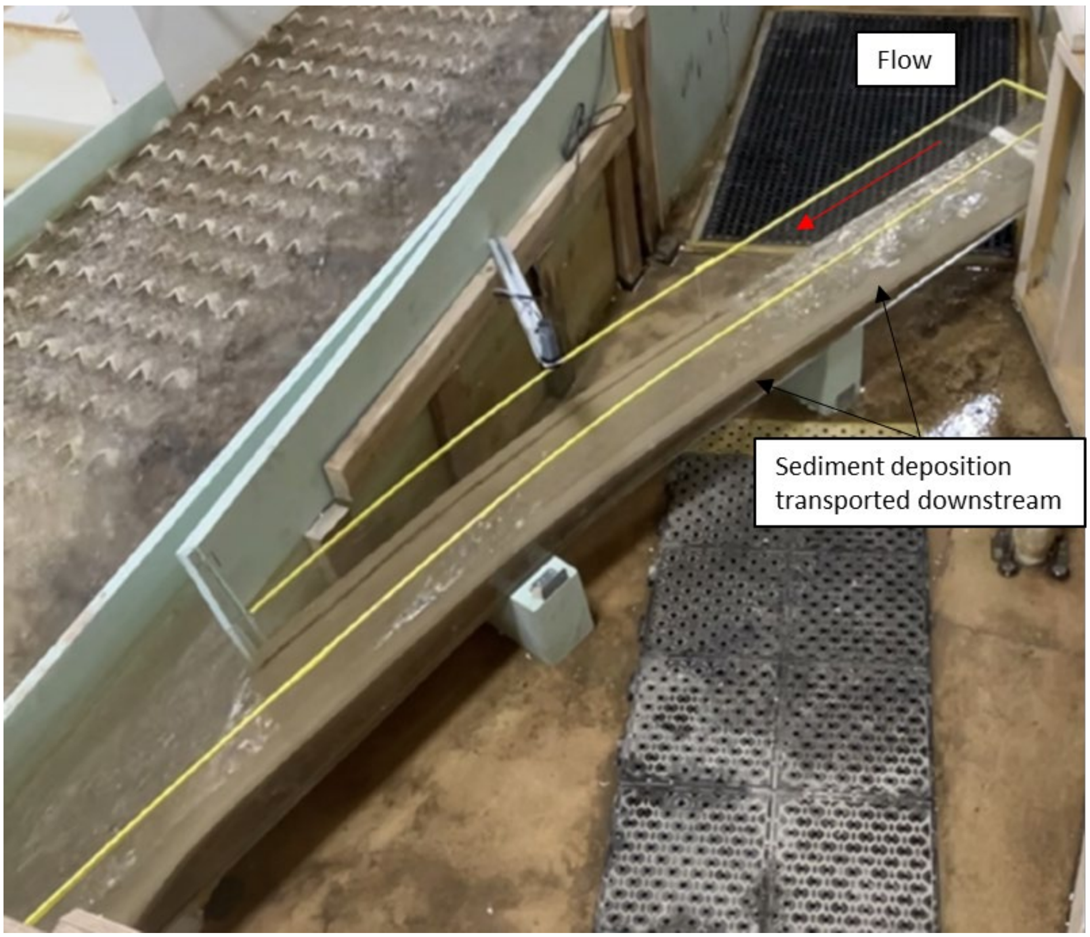


Figure 114. Photograph showing sediment transport within the sluicing channel by modulating the flows within the desander at a tailwater elevation of 145 ft.

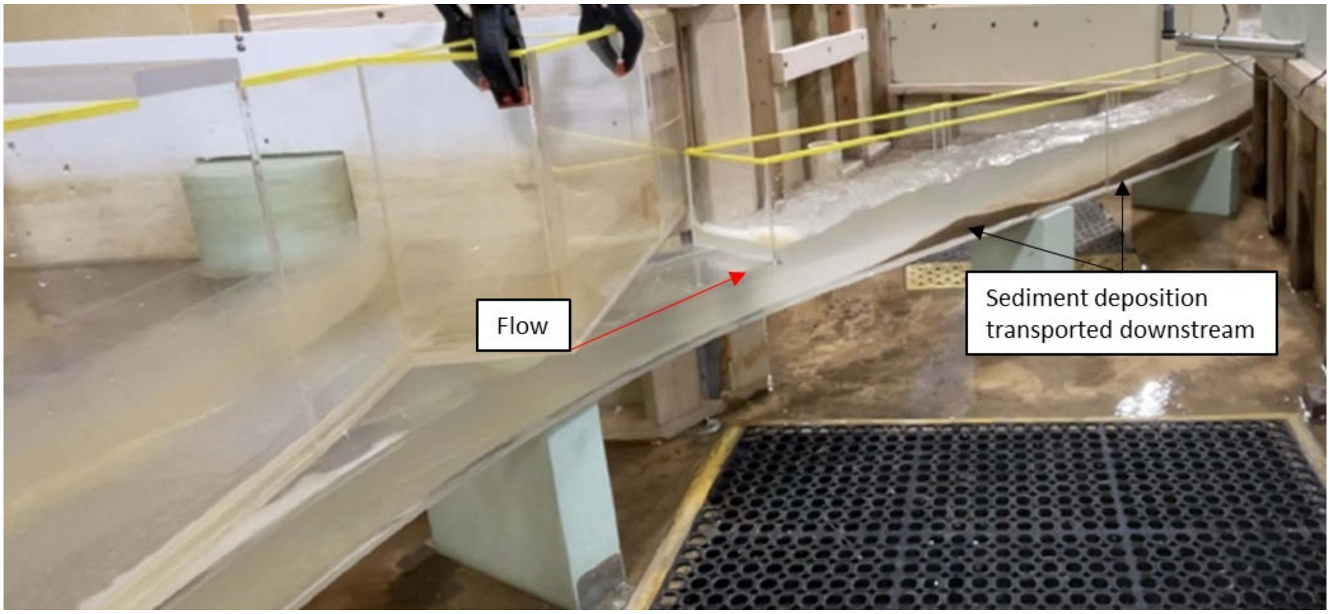


Figure 115. Photograph showing the water surface and sediment transport within the sluicing channel by modulating the flows within the desander at a tailwater elevation of 145 ft. Culvert is clear of sediment.

Groyne Sediment Features

Tests were conducted with river groyne structures made of 3-ft to 4-ft diameter riprap spaced along the left riverbank upstream of the canal intake. A comparison of water level and discharge measurements for 6,000, 3,000, and 1,500 ft^3/s is shown in Table 23 for configurations with and without these groyne structures. Groyne structures did not produce a significant difference in flow split results. There was no flow over the dam crest at 1,500 ft^3/s and flow splits between the dam and hardened ramp were similar for both configurations. Flow splits at 3,000 ft^3/s were similar to design development tests of configurations without a flushing channel, with more flow through the hardened ramp than baseline test results. A similar result is shown at 6,000 ft^3/s but the flow split became more balanced as water levels increased and utilized more of the river channel on the right side toward the dam.

Table 23. Flow split comparison with and without upstream channel training features (rock groynes along left bank).

Flow Split Comparisons				
	River	Diversion	Dam	Hardened Ramp
6000 ft^3 /s				
No Groynes	6,219	809	1,551	3,859
Groynes	6,003	849	1,723	3,432
3000 ft^3/s				
No Groynes	2,902	833	262	1,808
Groynes	2,945	834	297	1,814
1500 ft^3/s				
No Groynes	1,495	847	0	649
Groynes	1,492	853	0	639

Observations of flow patterns with dye, photos, and bed difference maps of the quasi-equilibrium sediment patterns for the upstream riverbank are shown in Figure 116 through Figure 124. These results include flows of 6,000, 3,000, and 1,500 ft^3/s. The difference map of 6,000 ft^3/s shows a significant reduction in bed elevations upstream of the hardened ramp especially near the right wall (Figure 118). This difference was not observed for 3,000 ft^3/s and 1,500 ft^3/s. Results showed that the groynes generally produced additional sediment deposition along the left bank and reduced bed elevations in the center and right side of the active flow channel upstream. Bedforms at the hardened ramp exit and canal intake were not significantly affected. These differences in bed elevations were not sufficient to notably alter flow patterns and flow splits as previously shown.

6,000 ft^3/s – Groyne Features Installed

Figure 116. Photographs of flows with dye approaching the hardened ramp without groynes (top) and with groynes (bottom) at 6,000 ft^3/s.

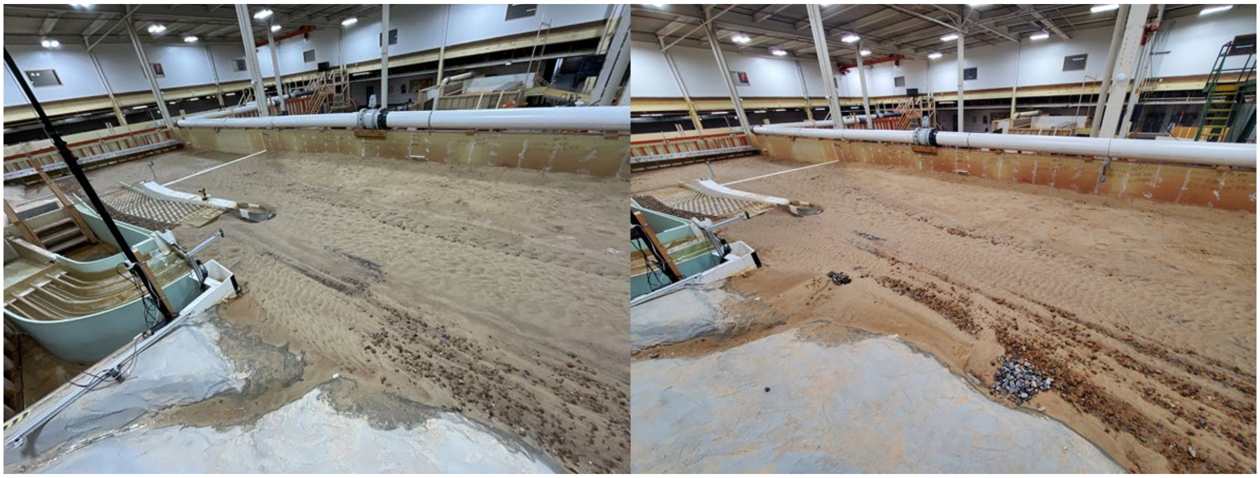


Figure 117. Photographs of sediment bedforms upstream of the hardened ramp without groynes (left) and with groynes (right) at 6,000 ft^3/s.

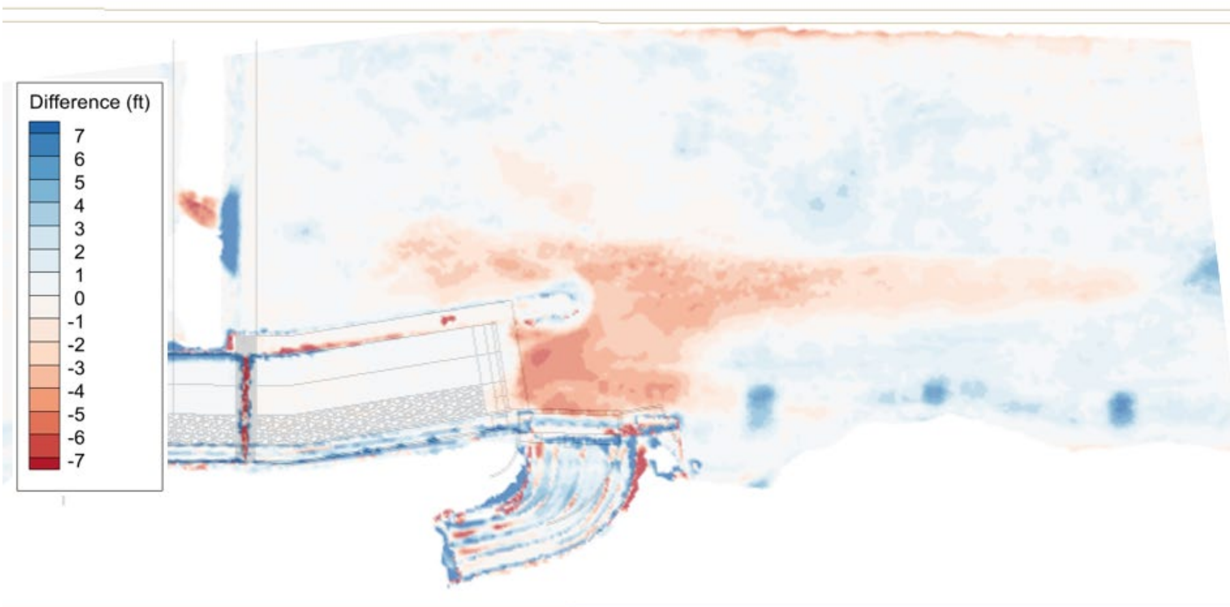


Figure 118. Topography difference contour map (with groynes minus without groynes) of sediment bedforms upstream of the hardened ramp at 6,000 ft^3/s.

3,000 ft³/s – Groyne Features Installed

Figure 119. Photographs of flows with dye approaching the hardened ramp without groynes (top) and with groynes (bottom) at 3,000 ft^3/s.

Figure 120. Photographs of sediment bedforms upstream of the hardened ramp without groynes (left) and with groynes (right) at 3,000 ft^3/s.

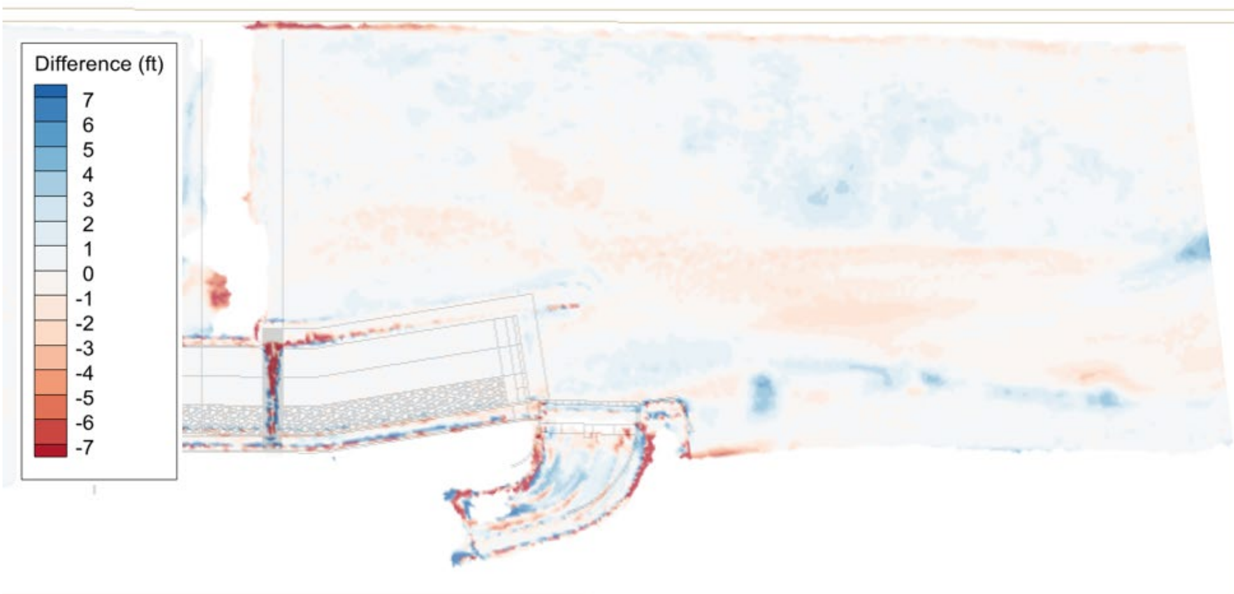


Figure 121. Topography difference contour map (with groynes minus without groynes) of sediment bedforms upstream of the hardened ramp at 3,000 ft^3/s.

1,500 ft^3/s – Groyne Features Installed

Figure 122. Photographs of flows with dye approaching the hardened ramp without groynes (top) and with groynes (bottom) at 1,500 ft^3/s.

Figure 123. Photographs of sediment bedforms upstream of the hardened ramp without groynes (left) and with groynes (right) at 1,500 ft^3/s.

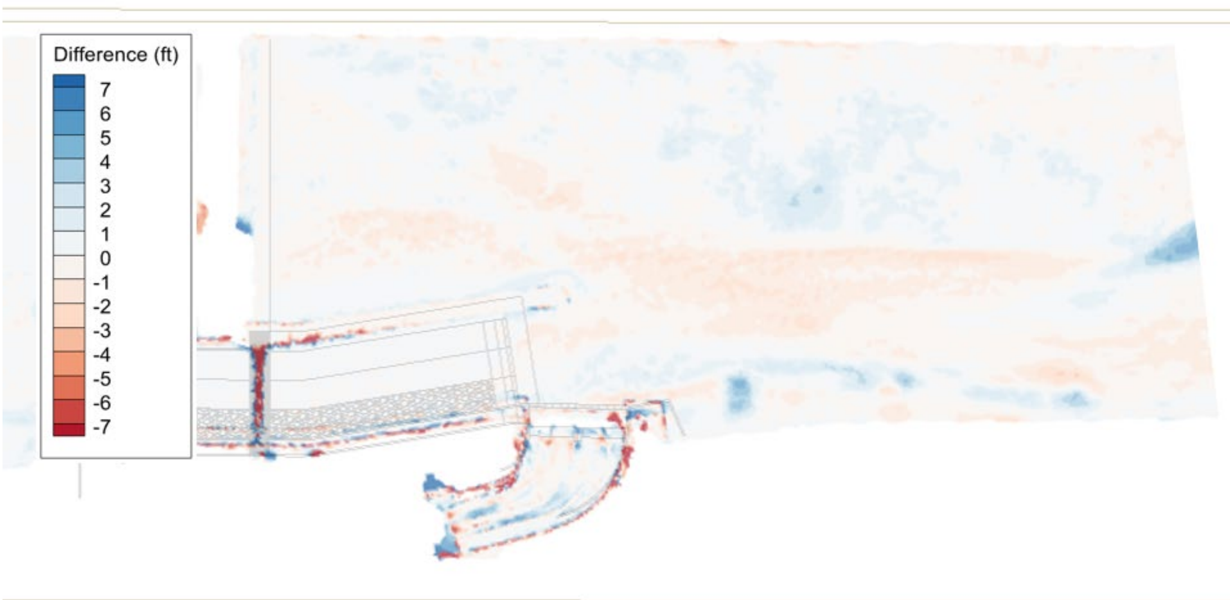


Figure 124. Topography difference contour map (with groynes minus without groynes) of sediment bedforms upstream of the hardened ramp at 1,500 ft^3/s.

Since test results and observations of groyne features along the left bank did not show any major differences in hydraulic conditions and sediment patterns no further testing was pursued.

Hardened Ramp Fish Passage

Original Design and Roughness Modifications

The hardened ramp contains two sections to provide fish passage over a range of flow conditions. For low flows less than 600 ft^3/s, a 30-ft wide triangular low-flow section was designed for fish passage. This low-flow section was lined with approximately 1- to 2-ft-diameter rocks with larger 3-ft-diameter rocks placed every 20 ft. As flows rise, adjacent to the low-flow channel is a 60-ft-wide baffled ramp designed with 5-ft-wide vee-shaped sloped steel baffle plates with a 2.5-ft slot width. In between and behind these baffles, ¾- to 1-ft-diameter rocks were placed to increase roughness. These rock placement patterns continued until the four upstream-most rows of baffles (Figure 128). This design represents the original configuration of the hardened ramp and was tested for fish passage at both the 1:12 and 1:24 scale (Appendix B: Summary of 1:24 Scale Baseline Results and Appendix C: Summary of 1:12 Scale Baseline Results).

Figure 125. Original hardened ramp roughness configuration.

Baseline testing related to the hardened ramp consisted of PIV analysis in the area immediately upstream of the hardened ramp fish exit and ADV analysis of the flows over the hardened ramp gates. The baseline flow tests ranged from 270 to 6,000 ft^3/s. The overall trend of these tests showed that velocities upstream of the hardened ramp exit ranged from 4 – 7 ft/s, with velocities increasing to 8 – 10 ft/s as flow contracted into the hardened ramp (Figure 126). At the downstream fish entrance to the hardened ramp, only PIV data was collected. The lower quarter of the hardened ramp was submerged for all flows due to tailwater conditions. Upstream of this last quarter of the ramp, flow was restricted to the low flow section of the ramp at flows less than 600 ft^3/s. This produced relatively high velocities in the low flow section for all flows (Figure 127).

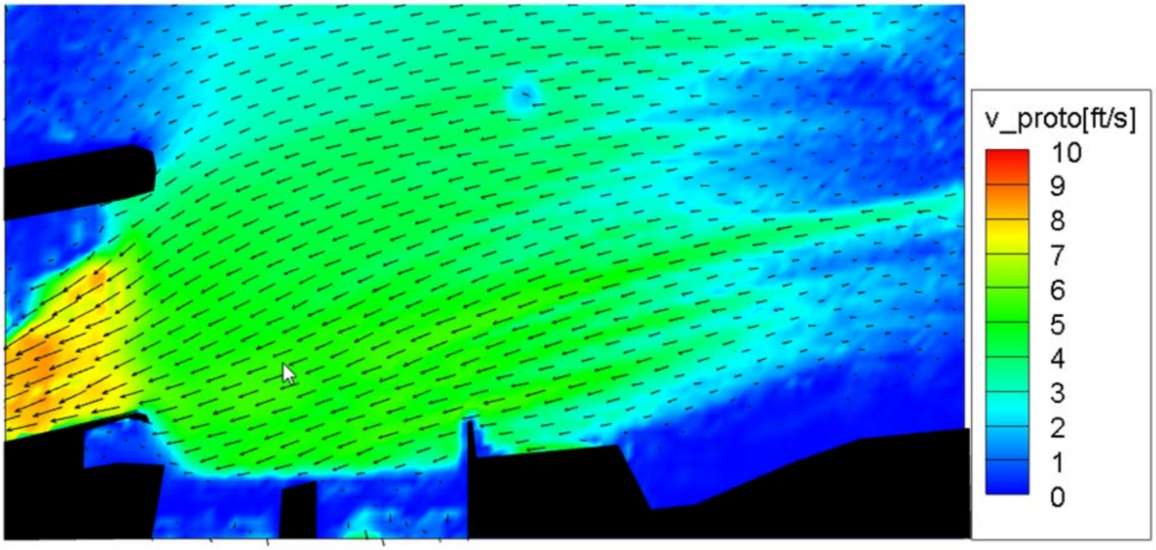


Figure 126. Sample PIV results of baseline testing at the fish exit of the hardened ramp at 3,000 ft^3/s. Dark blue portions of the figure without velocity vector arrows imply velocities less than 0.1 ft/s.

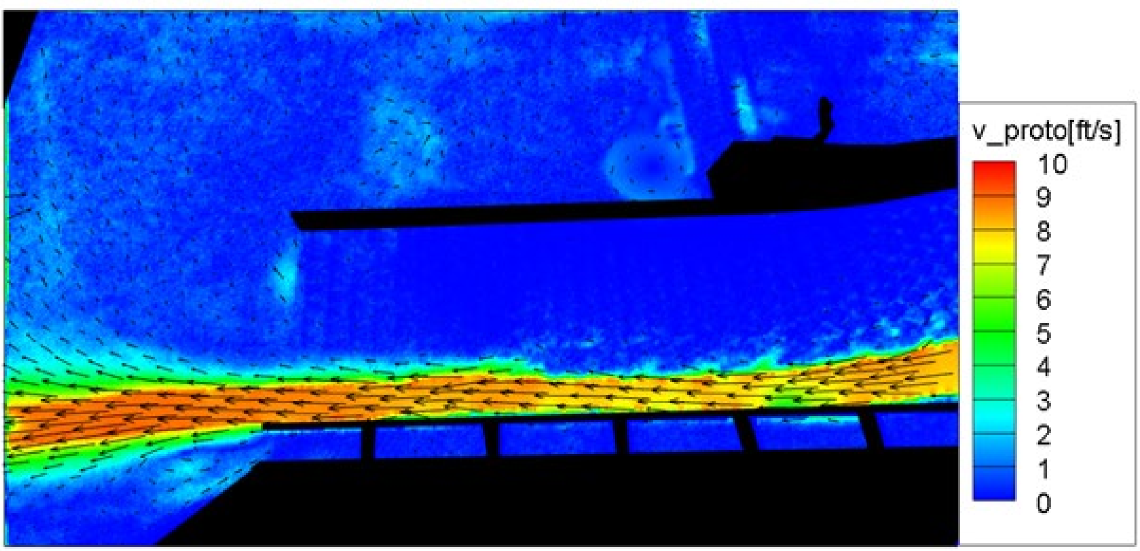


Figure 127. Sample PIV results of baseline testing at the fish entrance of the hardened ramp at 3,000 ft^3/s. Dark blue portions of the figure without velocity vector arrows on the right side of the hardened ramp imply velocities less than 0.1 ft/s.

After the initial baseline tests were completed, the hardened ramp low flow channel and baffled area was filled with rocks up to the hardened ramp gates (Figure 128). Velocity and depth data were collected at the hardened ramp gates and in the first four rows of baffles to compare the impact of the change in roughness in those areas. Changing the roughness in these locations did not have a significant impact on velocity or depth (Table 24). The additional rocks lowered the velocity over hardened ramp gates 1-3, but the lower velocity caused flow to spread over gate 4, causing an increase in velocity over gate 4. This pattern of lowered velocities in central sections but increased velocities at the edge of wetted area was also observed behind the first row of baffles and in the low flow section of the hardened ramp. The rocks added in these areas remained in place for the duration of testing.

Figure 128. Hardened ramp with 1- to 2-ft-diameter rocks filled in to just downstream of the hardened ramp gates (looking downstream).

Table 24. Hardened ramp roughness testing at 3,000 ft^3/s. Rocks were applied to the most upstream portion of the hardened ramp and compared to the baseline design for velocity and depth. Depths were not recorded in the baffled area.

Location		**Baseline**		**With Additional Rocks**	
		Velocity	**Depth**	**Velocity**	**Depth**
-	-	*ft/s*	*ft*	*ft/s*	*ft*
Hardened Ramp	Gate 1	4.4	6	4.2	6
	Gate 2	4.8	5.1*	4.2	5.8
	Gate 3	3.9	2.2	3.7	3.6
	Gate 4	1.2	2.5	2	3
Low-Flow Section	Low-Flow Left	5.9	5.4	5.9	5
	Low-Flow Center	4.3	3.6	5.1	4.6
Baffles	Center of Baffle Section	1.1	**	0.7	**
* Measurement was taken in an area with sediment deposition that impacted depth. ** Depths were not measured in the baffled area					

Low Flow Section Fish Passage

After the roughness on the upstream portion of the hardened ramp was increased, large rocks were added to the low flow section of the ramp to improve resting conditions during low flows of 600 ft^3/s or less. These rocks were larger than the original lining of the hardened ramp, with the largest rock size representing 30 – 40 inches prototype. The first iteration of this design, referred to as Version 1, included the installation of one "cycle" of rocks. Each cycle represented a 40-ft section of the hardened ramp before it is repeated (Figure 129 and Figure 130). Version 1 was tested at 100 – 400 ft^3/s, with only velocity measurements made. Another iteration of rock design, Version 2, was installed for the entire low flow section of the hardened ramp and tested for flows ranging from 100 – 600 ft^3/s with both PIV surface data collected and point velocity data collected with a Nixon meter due to the low depth of flow (Figure 131 and Figure 132).

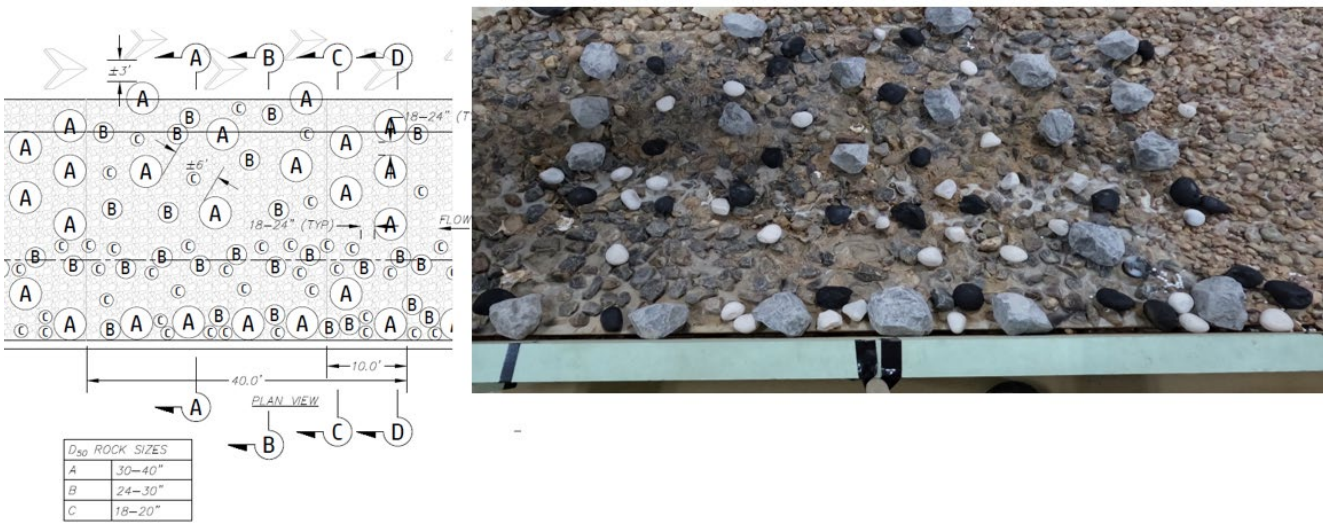


Figure 129. Version 1 of the low-flow section of rocks added in for one cycle (40-ft) on the hardened ramp, shown in comparison to the original design.

Figure 130. Version 1 of the low flow section of rocks added in for one cycle (40-ft) on the hardened ramp (looking downstream).

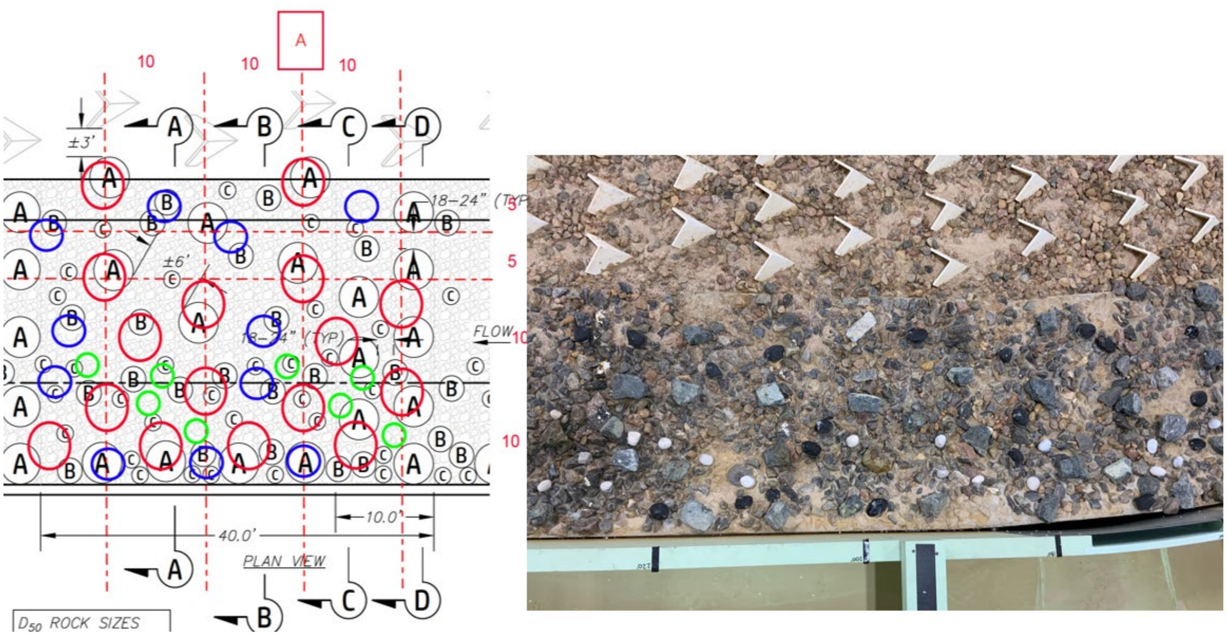


Figure 131. Version 2 of low flow channel rocks added in for the entire hardened ramp.

Figure 132. Version 2 of low flow channel rocks shown extending down the hardened ramp.

Version 1 and Version 2 differed in both the quantity and placement of the rocks (Table 25). While the largest size of rock, 30 – 40 inches, was placed in the same quantity between the two designs, Version 2 included less of the two smaller sizes than Version 1. Version 1 had significantly more rocks in the left edge of the low flow section of the hardened ramp. However, this area was often too shallow for fish passage at the lower flow rates. Version 2 placed the largest rock size in the centerline of the low flow section of the hardened ramp, while Version 1 relied on the smaller rock in the centerline.

Table 25. Quantities of each size of rock for Versions 1 and 2 of the low-flow section improvements.

	Version 1 Rock Quantity	***Version 2 Rock Quantity***
Size A (30-40")	16	16
Size B (24-30")	20	11
Size C (18-20")	30	8

When comparing velocities and depths between Version 1 and Version 2 at the centerline of the low flow section of the hardened ramp, Version 2 consistently performed better than Version 1 (Table 26). Peak velocities were reduced from approximately 10 ft/s to slightly over 8 ft/s with all depths exceeding 1 ft, even at the lower flow rates. There was a diversity of fish passage options at lower velocities on either side of the centerline (Figure 133 through Figure 150).

Table 26. Comparison of velocities and depths between Versions 1 and 2 of the low flow section improvements.

	Version 1 (Centerline)		Version 2 (Centerline)	
River Flow	***Velocity***	***Depth***	***Velocity***	***Depth***
ft^3/s	*ft/s*	*ft*	*ft/s*	*ft*
400	10.4	2.5	8.5	3.8
300	10.3	2.0	8.1	3.7
200	6.8	1.5	5.4	2.5

When comparing Version 2 of the low-flow section improvements to baseline testing, the flow over the hardened ramp gates at the fishway exit and the downstream entrance of the ramp can be compared. The velocity data do not show a significant reduction in velocities over the hardened ramp gates (Table 27). The difference in velocities over gates 1 and 2 likely comes from the difference in flow splits. For the baseline test, 170 ft^3/s passed down the hardened ramp, while the remaining flow was diverted into the intake. For the low flow section rock tests, the intake was not active during the test, so all the flow was concentrated down the hardened ramp.

Table 27. Comparison of velocities at 200 ft³/s on the baseline hardened ramp configuration to Version 2 of the hardened ramp low-flow section improvements. In baseline tests, the river flow was set to approximately 270 ft³/s, with approximately 100 ft³/s diverted through the intake. For the low flow design development tests, no flow was diverted through the intake.

Hardened Ramp Flow	Hardened Ramp Location	Baseline	Hardened Ramp V2
		Velocity	Velocity
ft³/s	-	*ft/s*	*ft/s*
200*	Gate 1	1.9	1.0
	Gate 2	1.0	2.3
*At baseline tests, the flow was approximately 170 ft³/s down the hardened ramp, with the remaining flow going through the intake.			

Overall, the addition of large rocks successfully lowered velocities to under 8 ft/s for the majority of the low flow section of the hardened ramp during flow events less than 600 ft³/s (Figure 133 through Figure 150). As opposed to Version 1 with many small rocks near the centerline of the low flow channel (i.e.- lowest point of low flow channel), Version 2 concentrated a few large rocks along the centerline. Version 1 also had more rocks in the upper left side of the low flow section of the channel. This area was often too shallow for fish passage at low flows, whether rocks were present or not. As Version 2 focused on having rocks in areas of high velocity (such as the centerline), it was more efficient at reducing velocities with less rocks needed.

The baffled portion of the hardened ramp began to activate at 300 ft³/s. However, baffles were unable to accommodate fish passage due to depth constraints (depths under 1 ft), until approximately 500 ft³/s. The exception to this was the most downstream quarter of the hardened ramp. Due to tailwater conditions, this portion of the ramp was submerged at all flow conditions, with or without the addition of large rocks in the low flow channel.

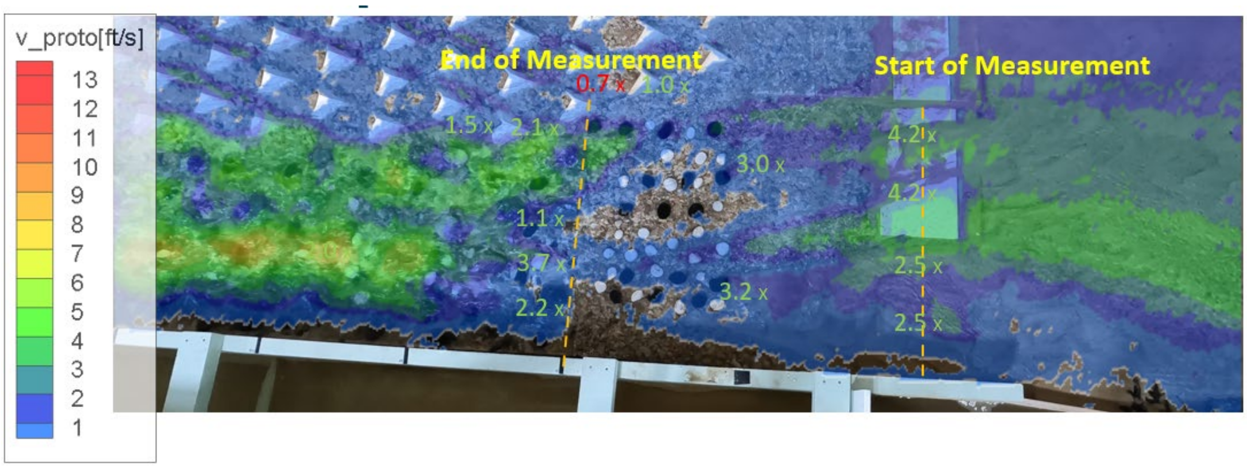


Figure 133. Upstream hardened ramp configuration for fish passage at 600 ft³/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent. Depths were shallow at the left-most gate of the hardened ramp due to separation of flow around the edge of the flushing channel.

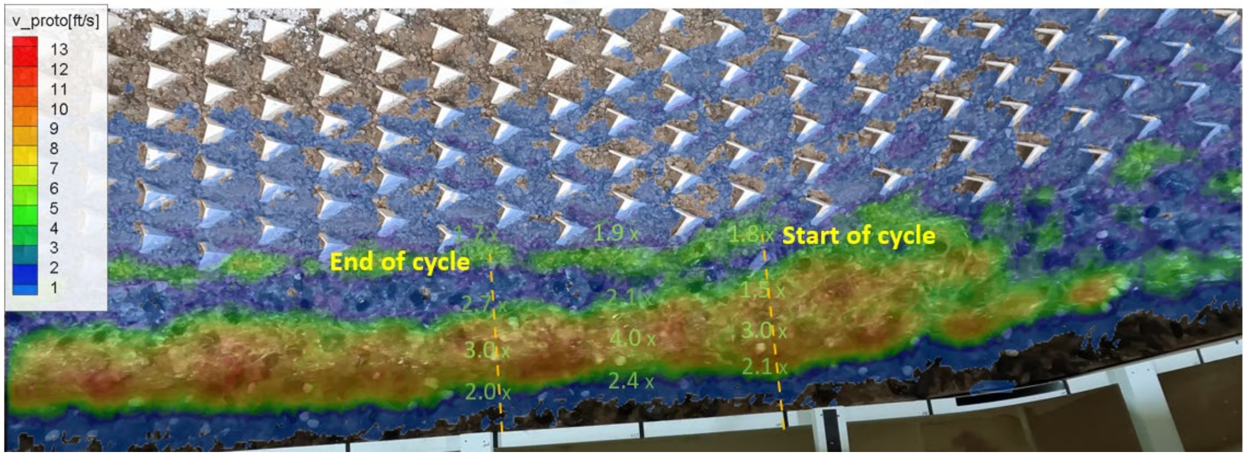


Figure 134. Mid-ramp hardened ramp configuration for fish passage at 600 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent.

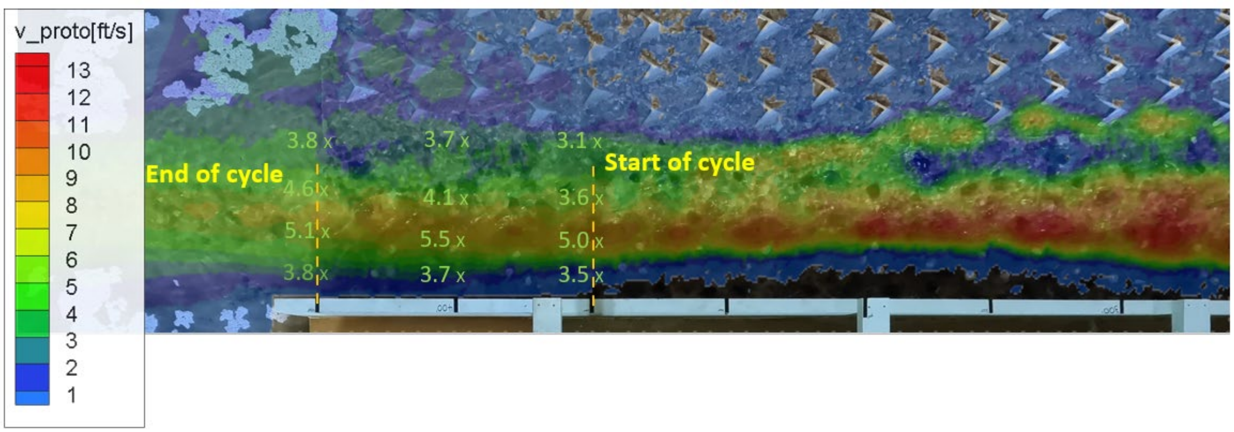


Figure 135. Downstream hardened ramp configuration for fish passage at 600 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent.

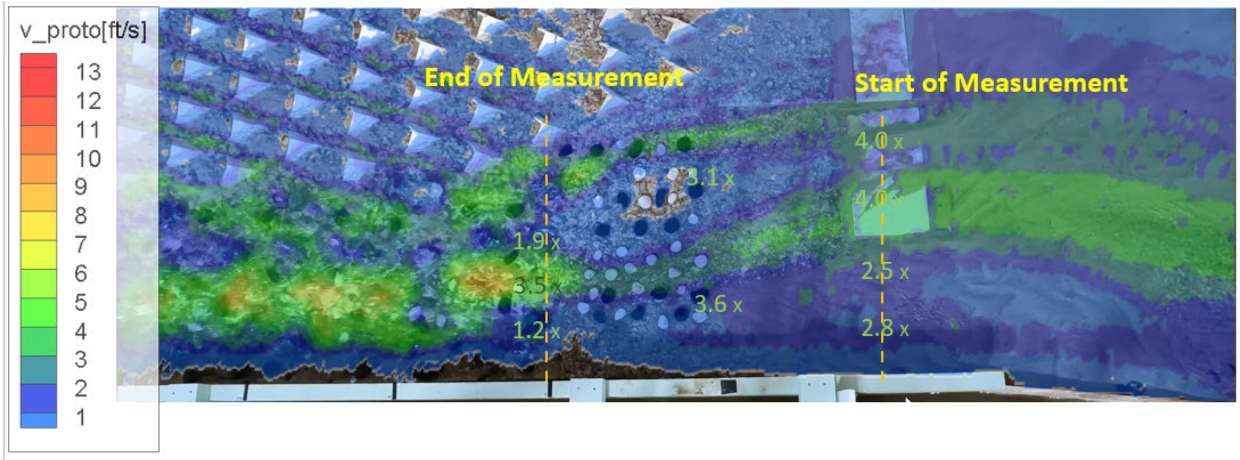


Figure 136. Upstream hardened ramp configuration for fish passage at 500 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent. Depths were shallow at the left-most gate of the hardened ramp due to sediment deposition on the gate and separation of flow around the edge of the flushing channel.

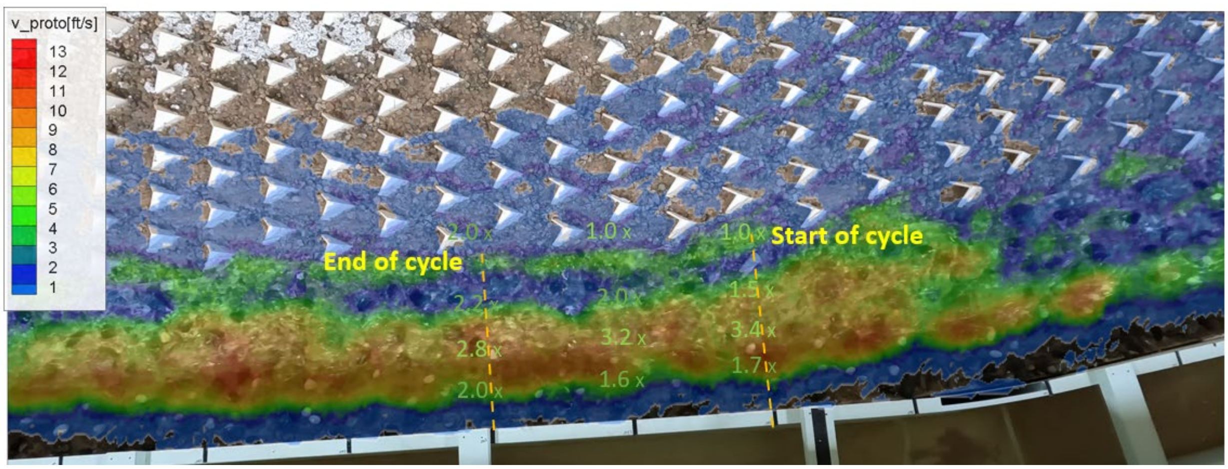


Figure 137. Mid-ramp hardened ramp configuration for fish passage at 500 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent.

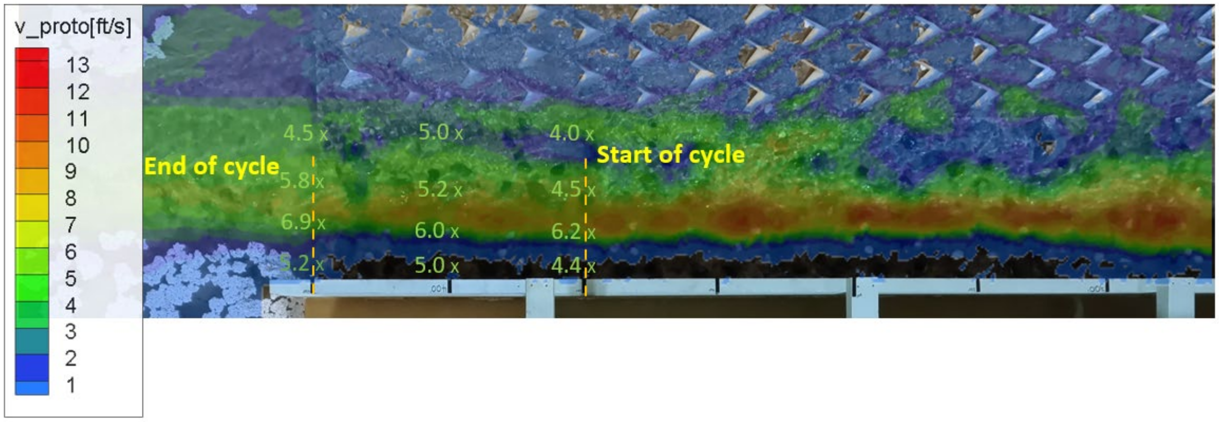


Figure 138. Downstream hardened ramp configuration for fish passage at 500 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent.

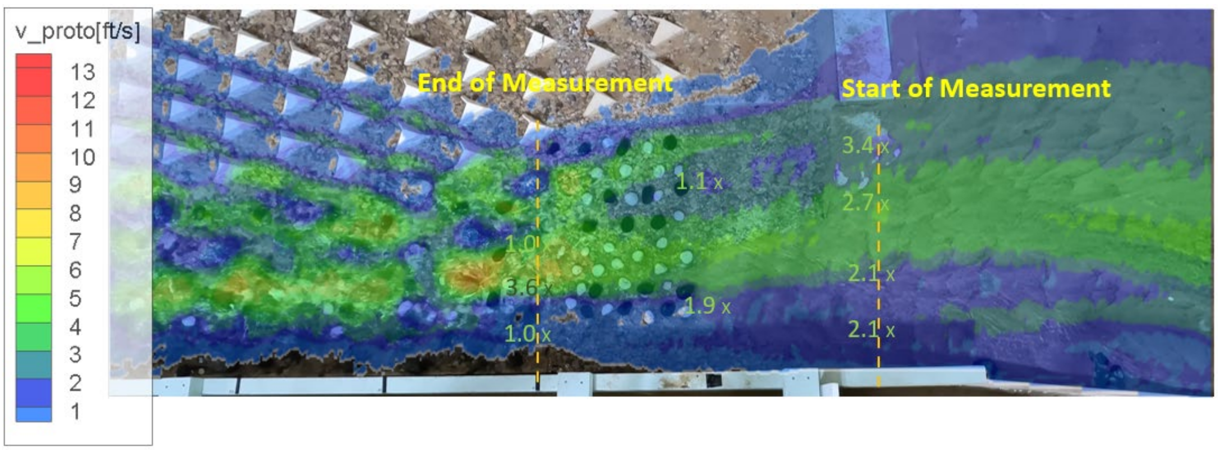


Figure 139. Upstream hardened ramp configuration for fish passage at 400 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent. Depths were shallow at the left-most gate of the hardened ramp due separation of flow around the edge of the flushing channel.

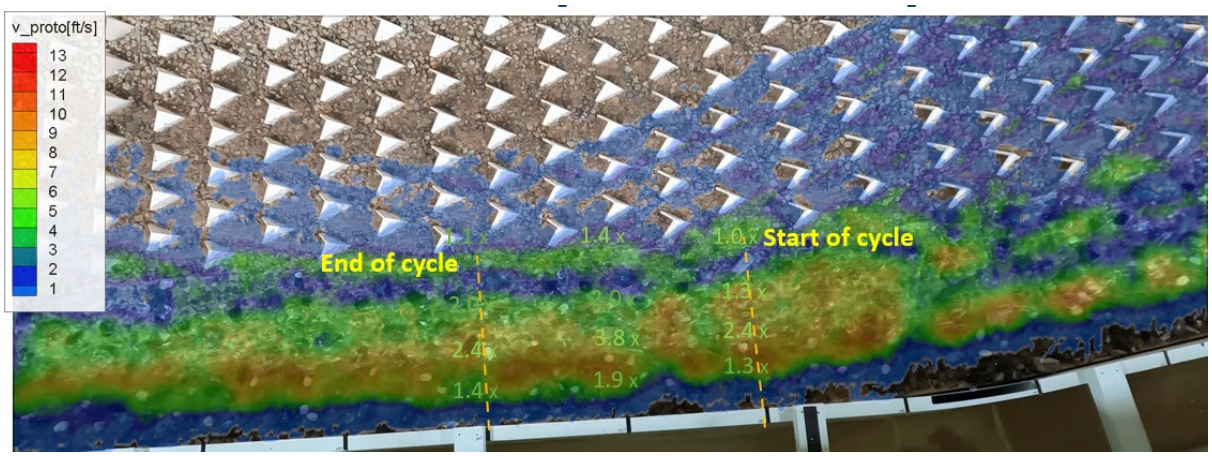


Figure 140. Mid-ramp hardened ramp configuration for fish passage at 400 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent.

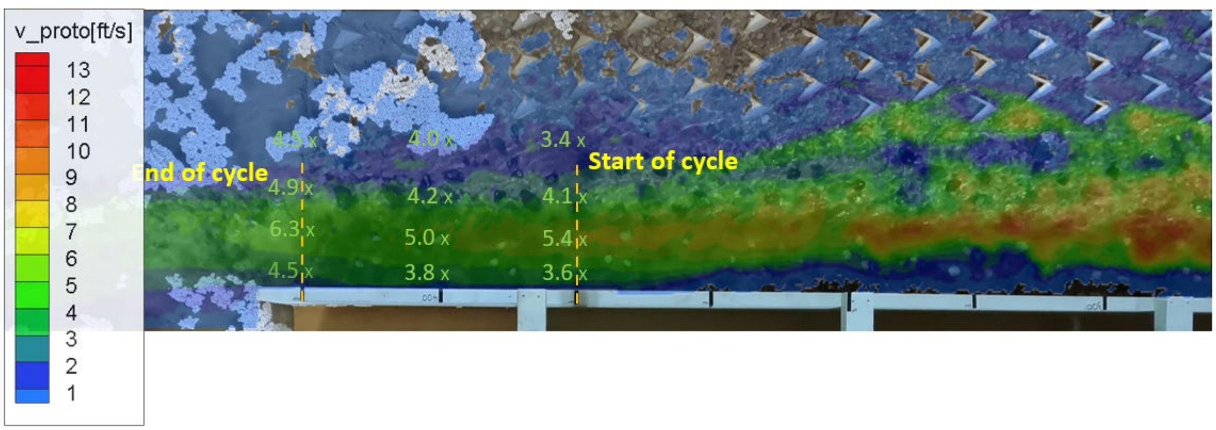


Figure 141. Downstream hardened ramp configuration for fish passage at 400 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent.

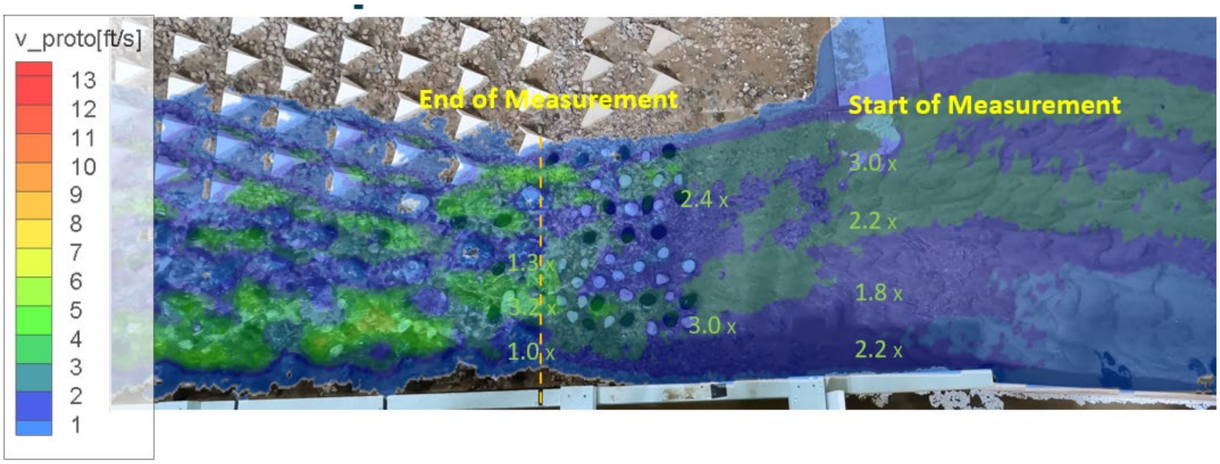


Figure 142. Upstream hardened ramp configuration for fish passage at 300 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent. Depths were shallow at the left-most gate of the hardened ramp due to sediment deposition on the gate and separation of flow around the edge of the flushing channel.

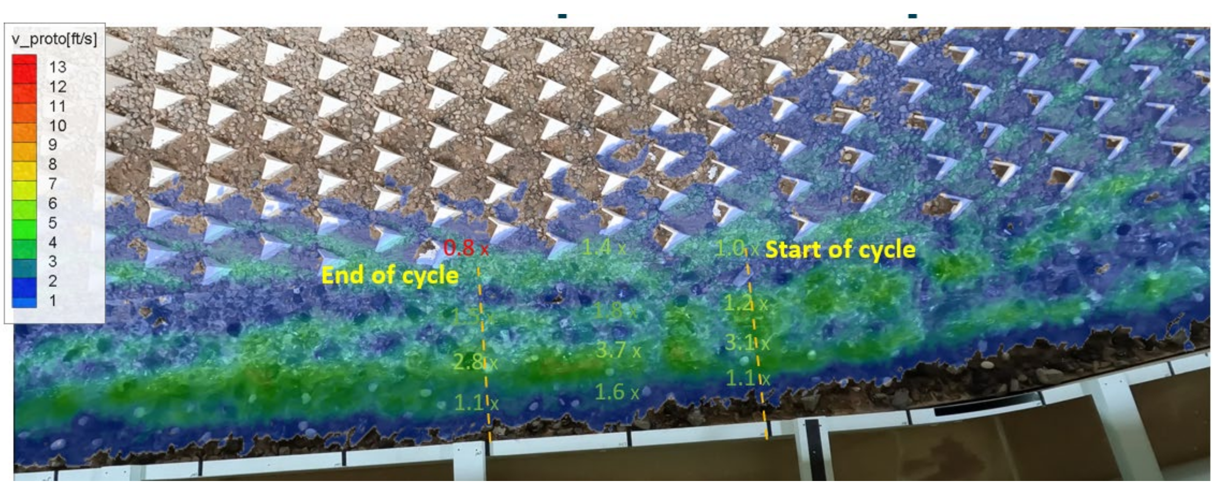


Figure 143. Mid-ramp hardened ramp configuration for fish passage at 300 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent.

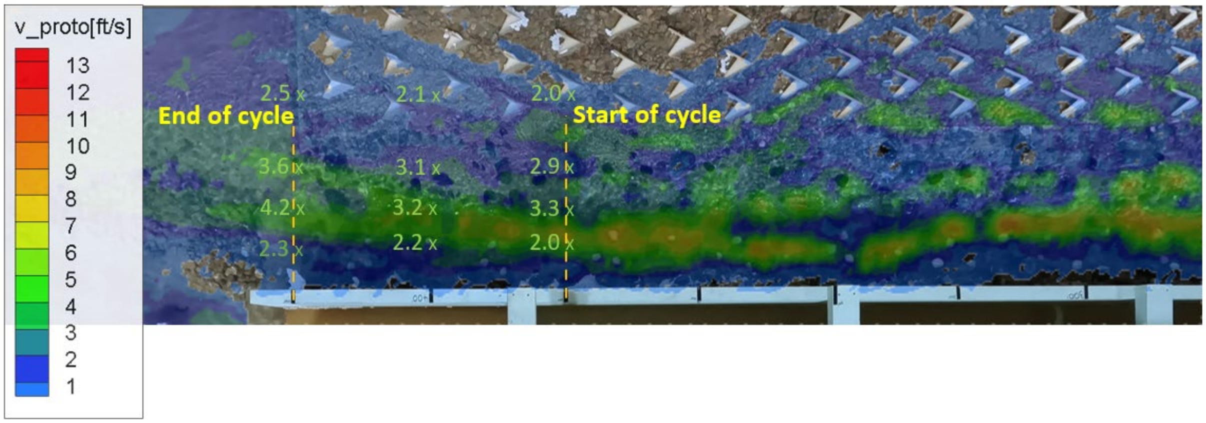


Figure 144. Downstream hardened ramp configuration for fish passage at 300 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent.

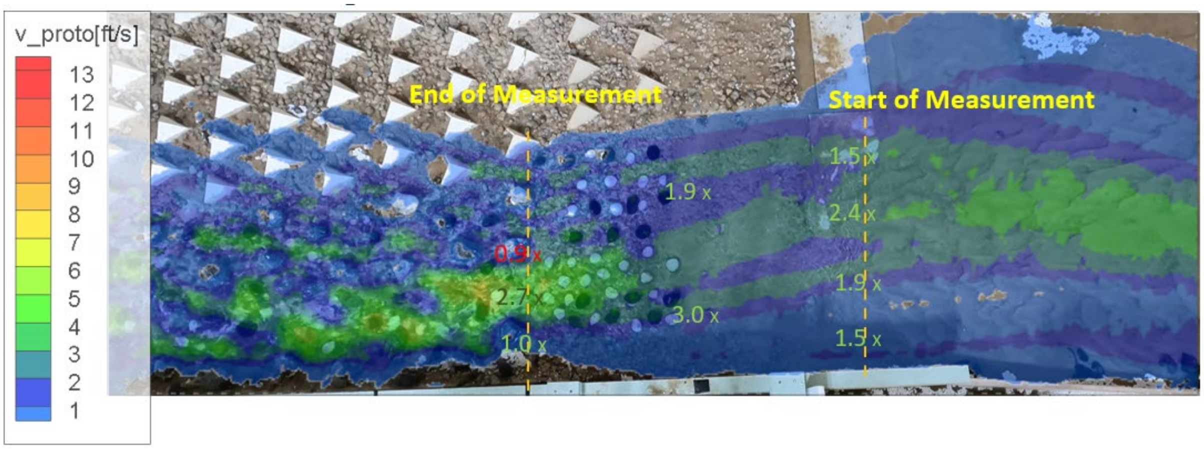


Figure 145. Upstream hardened ramp configuration for fish passage at 200 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent.

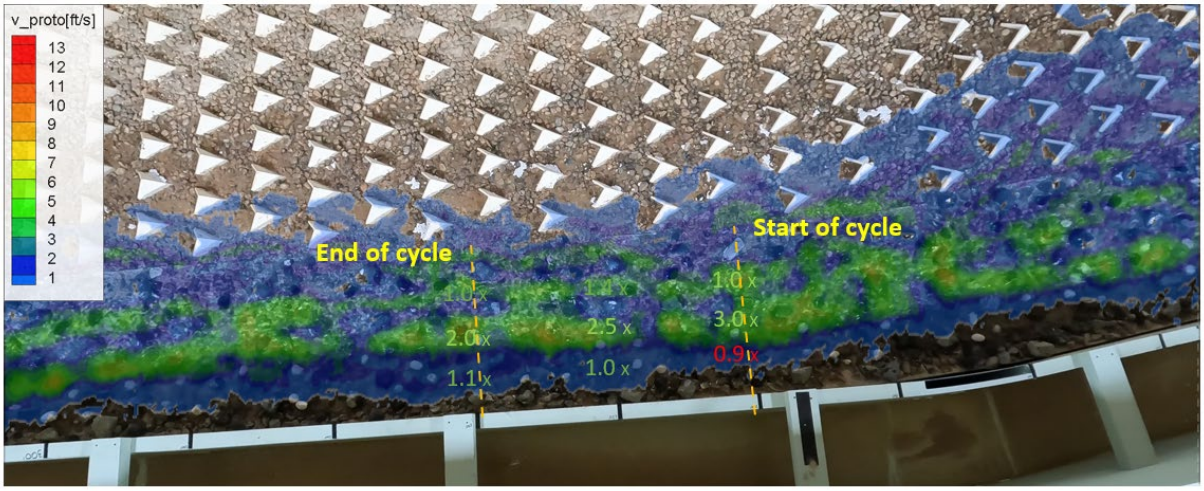


Figure 146. Mid-ramp hardened ramp configuration for fish passage at 200 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent.

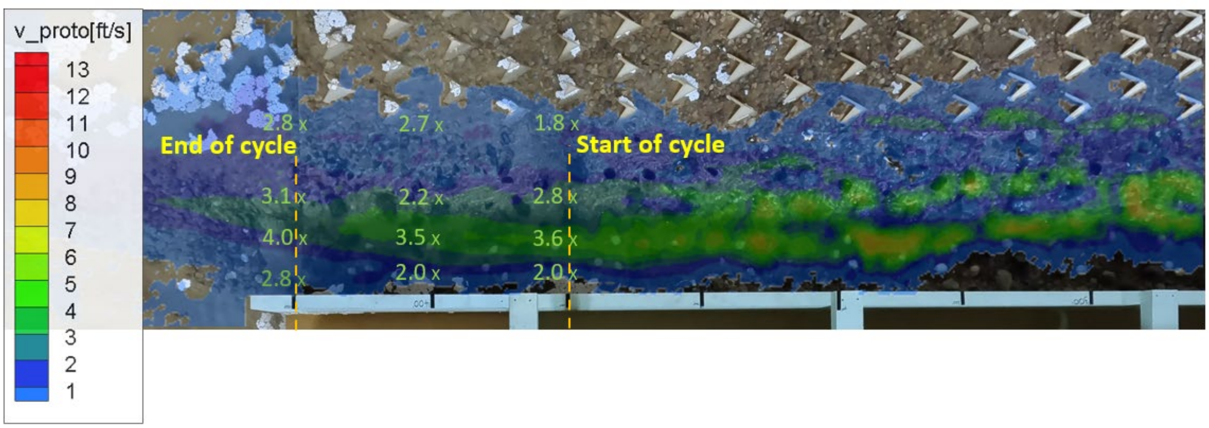


Figure 147. Downstream hardened ramp configuration for fish passage at 200 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent.

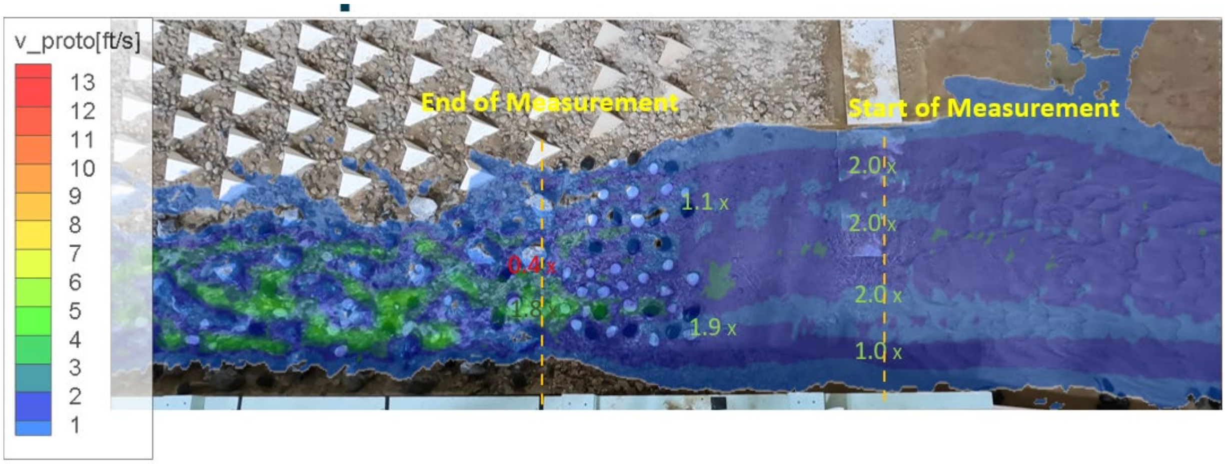


Figure 148. Upstream hardened ramp configuration for fish passage at 100 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent.

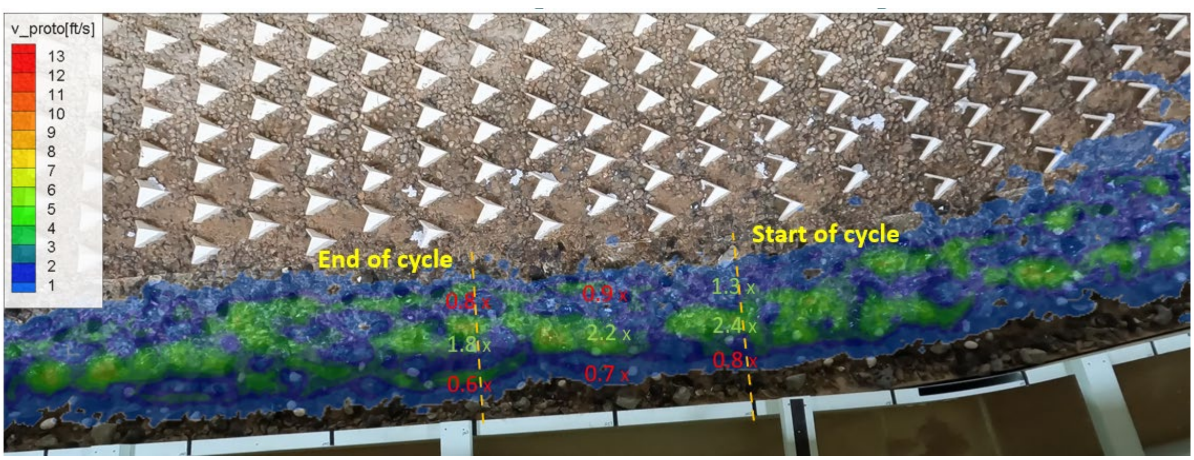


Figure 149. Mid -ramp configuration for fish passage at 100 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent.

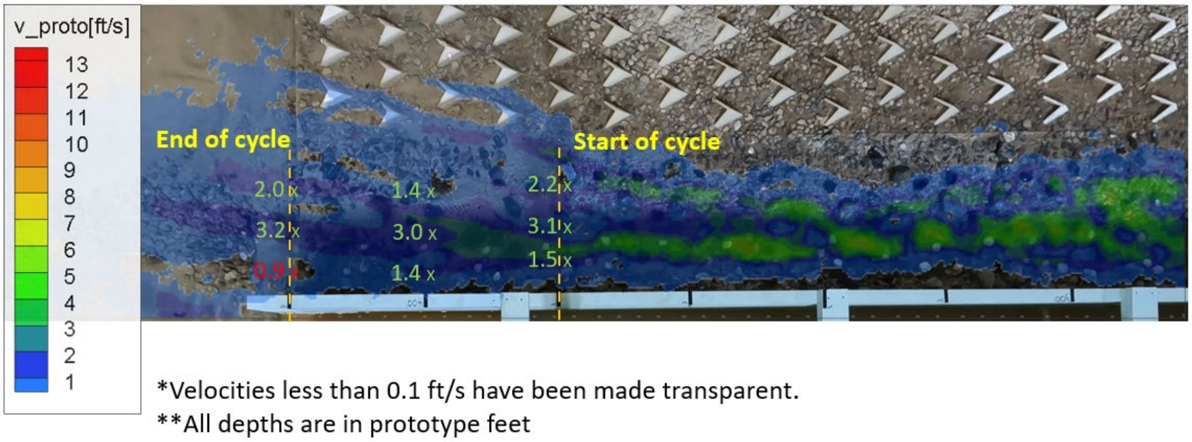


Figure 150. Downstream hardened ramp configuration for fish passage at 100 ft^3/s. Depths are shown in prototype feet with depths less than 1 ft denoted in red. Velocities less than 0.1 ft/s have been made transparent.

Castle Training Wall Configuration

The castle training wall is a critical feature of the flushing channel configuration for sediment management as presented in previous sections of the report. The castle training wall was also installed in the 1:12 model primarily to look at flow and sediment conditions fish passage at the exit of the hardened ramp for the flow range of 100 to 1,500 ft^3/s. At each of these flow rates, approximately half of the flow was diverted, while the other half went down the hardened ramp. The dam crest was dry for all test conditions in this flow range. At each flow, velocity, depth, and PIV data were recorded along with dye tests for flow visualization. As flows allowed, depths and velocities were recorded at four points along the castle training wall (Figure 151).

Water on the left side of the wall closest to the diversion intake and the right side leading to the hardened ramp had minimal cross flow through the slots until the downstream lowered notch for all flows (Figure 152 through Figure 161). Flow remained divided on each side of the castle training wall until the lowest notch, when flow would spill over towards the hardened ramp. This caused a scour hole immediately downstream of the lowered notch. As such, dye followed the flow on the intake side of the training wall before crossing over to the hardened ramp until flow increased to 1,500 ft^3/s. At 1,500 ft^3/s, all dye entered the intake before reaching the lowest notch, indicating a recirculation zone surrounding the lowered notch. This is reflected in the PIV and point velocity analysis (Table 28). On the intake side of the lower notch, velocity was lower (0.4 ft/s) at 1,500 ft^3/s than at 100 ft^3/s (1.1 ft/s).

For all flows under 1,500 ft^3/s, the water depth differential across the lower notch of the castle wall demonstrated that water depth was higher on the hardened ramp side of the training wall. This was largely due to sediment deposition patterns and flow patterns. On the hardened ramp side of the training wall, sediment was scoured out by the flow coming over the lower notch. However, on the intake side of the castle wall, sediment was approximately 1.1-ft deep in front of the lower notch.

The castle wall helped train the river to the left where the intake and hardened ramp are located when compared to configurations without a training wall, which was also seen in the 1:24 test results discussed in the section Normal Diverting Operations with a Flushing Channel – Test Results. This resulted in an increase in flow going over the hardened ramp. Velocities did not exceed 3 ft/s at any of the lower flow rates. Velocities peaked in front of the intake structure and gradually decreased until the lowered notch, where velocities increased again. A transition happened at 1,500 ft^3/s, where velocities remained relatively low in the downstream section of the channel, including upstream of the lowered notch as flow is pulled towards the intake, instead of down the hardened ramp.

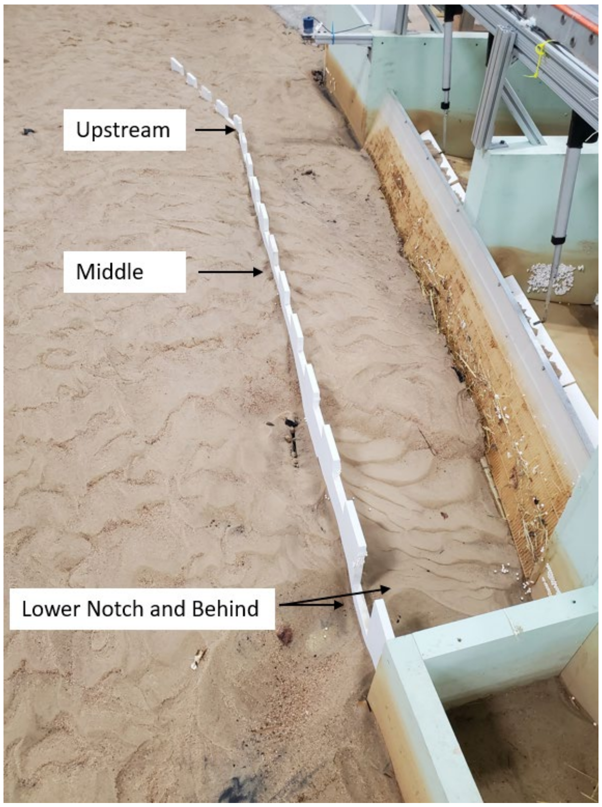
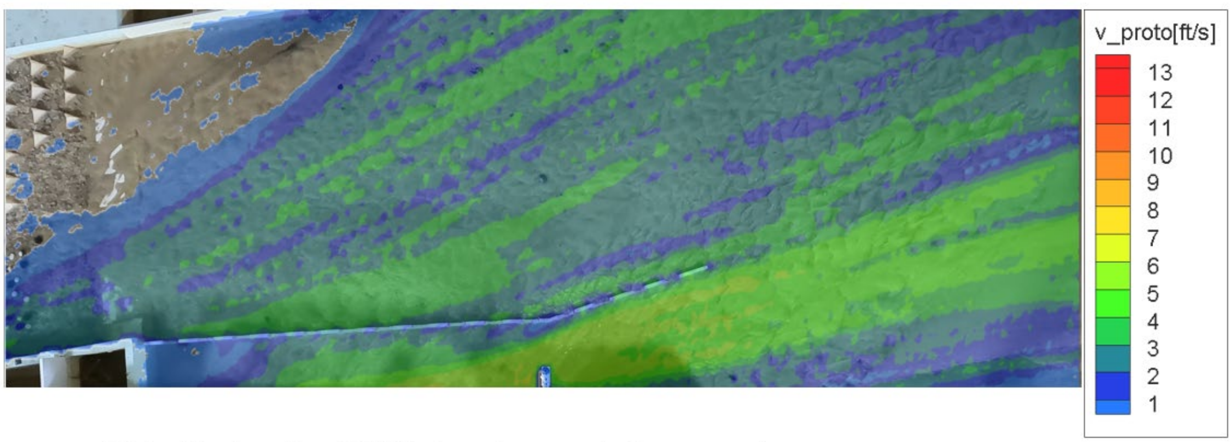


Figure 151. Castle training wall in the dry with location of velocity and depth measurements labeled. Scour can be observed immediately downstream of the lower notch.

Table 28. Castle training wall depths and velocities at a range and flows. The differential represents the difference between water depth on each side of the lower notch of the training wall.

River Flow	Castle Training Wall Location	Velocity	Depth	Differential
ft^3/s	-	*ft/s*	*ft*	*ft*
1,500	*Upstream*	1.9	2.6	-
	Middle	2.8	3.8	-
	Lower Notch	2.8	5.8	-1.5
	Behind Lower Notch	0.4	7.2	
800	*Upstream*	2.3	2.0	-
	Middle	2.4	3.1	-
	Lower Notch	1.7	6.5	0.6
	Behind Lower Notch	0.6	5.9	
400	*Upstream*	2.8	0.7	-
	Middle	2.7	2.0	-
	Lower Notch	1.8	5.2	0.2
	Behind Lower Notch	0.4	5.0	
200	*Upstream**	N/A	N/A	-
	Middle	2.0	1.1	-
	Lower Notch	2.2	4.7	0.5
	Behind Lower Notch	0.6	4.2	
100	*Upstream**	N/A	N/A	-
	*Middle**	N/A	N/A	-
	Lower Notch	3.0	4.2	0.8
	Behind Lower Notch	1.1	3.4	
** No flow on the hardened ramp side of the castle training wall at this point.*				

Figure 152. Dye test of the castle training wall structure upstream of intake. River flow was set to 1,500 ft^3/s, with approximately 750 ft^3/s diverted into the intake. At this flow, all dye was drawn into the intake. This was potentially caused by flow from the hardened ramp going towards the over the lowered notch at the downstream portion of the castle training wall and into the intake.



*Velocities less than 0.1 ft/s have been made transparent.

Figure 153. PIV results of the castle training wall structure upstream of intake. River flow was set to 1,500 ft^3/s, with approximately 750 ft^3/s diverted into the intake.

Figure 154. Dye test of the castle training wall structure upstream of intake. River flow was set to 800 ft^3/s, with approximately 400 ft^3/s diverted into the intake.

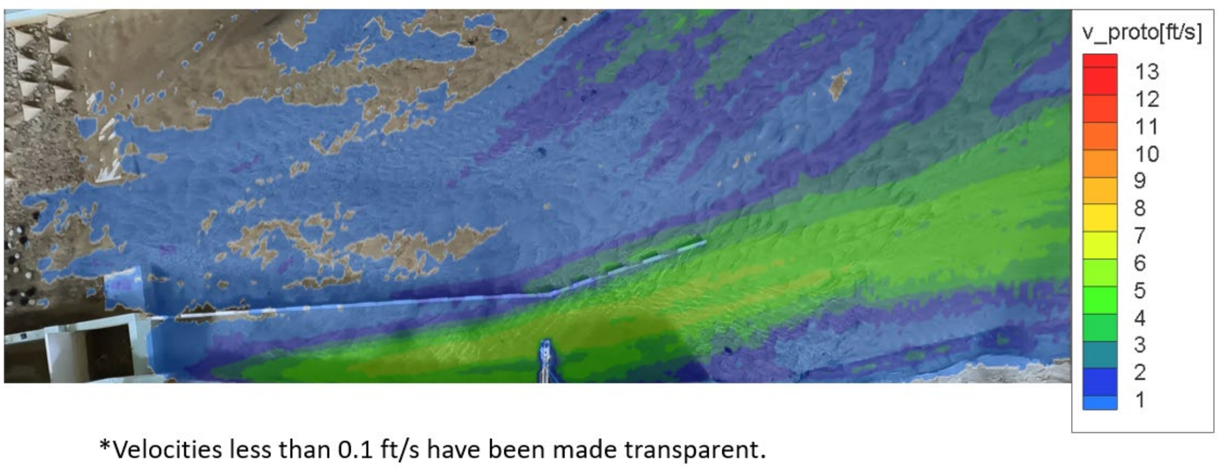


Figure 155. PIV results of the castle training wall structure upstream of intake. River flow was set to 800 ft^3/s, with approximately 400 ft^3/s diverted into the intake.

Figure 156. Dye test of the castle training wall structure upstream of intake. River flow was set to 400 ft^3/s, with approximately 200 ft^3/s diverted into the intake.

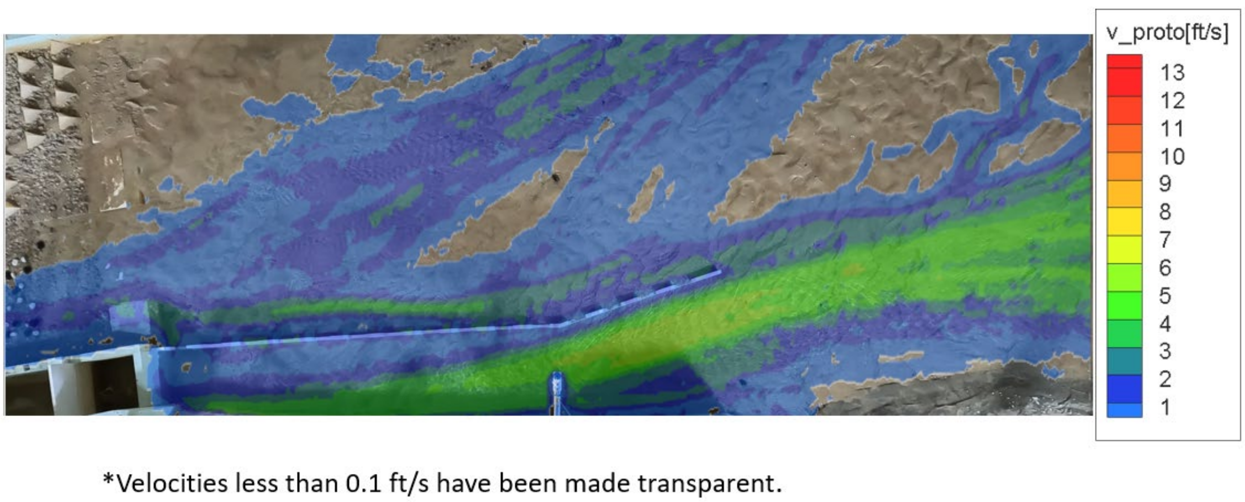
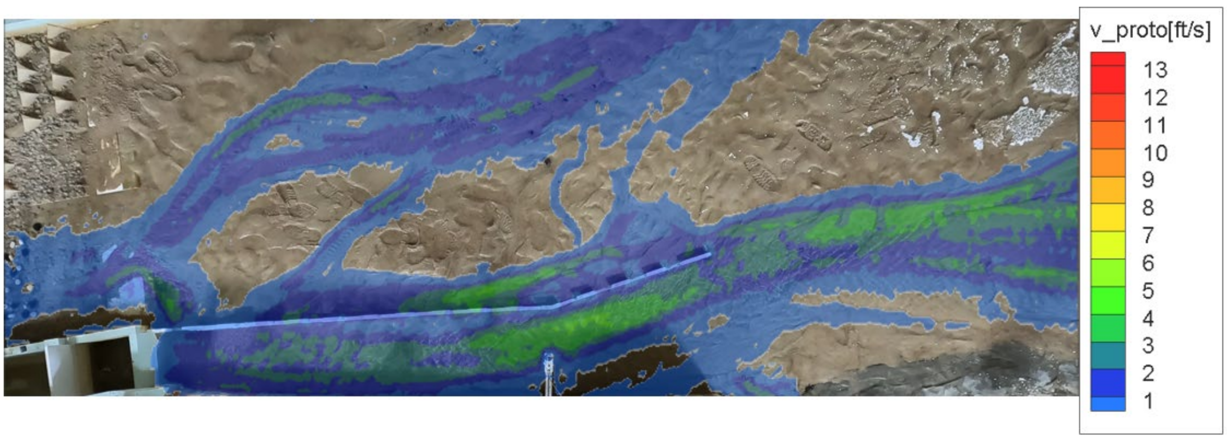


Figure 157. PIV results of the castle training wall structure upstream of intake. River flow was set to 400 ft^3/s, with approximately 200 ft^3/s diverted into the intake.

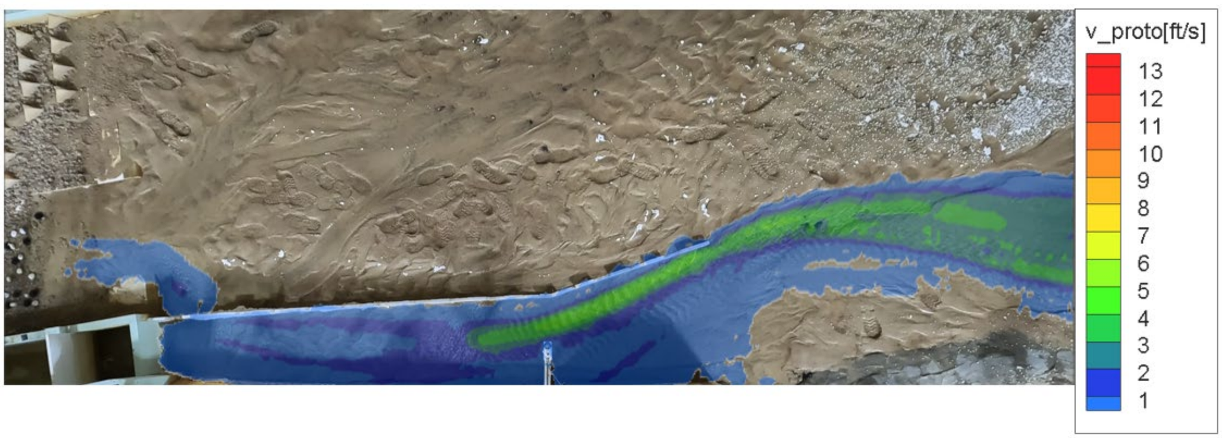
Figure 158. Dye test of the castle training wall structure upstream of intake. River flow was set to 200 ft^3/s, with approximately 100 ft^3/s diverted into the intake.



*Velocities less than 0.1 ft/s have been made transparent.

Figure 159. PIV results of the castle training wall structure upstream of intake. River flow was set to 200 ft^3/s, with approximately 100 ft^3/s diverted into the intake.

Figure 160. Dye test of the castle training wall structure upstream of intake. River flow was set to 100 ft^3/s, with approximately 50 ft^3/s diverted into the intake.



*Velocities less than 0.1 ft/s have been made transparent.

Figure 161. PIV results of castle training wall structure upstream of intake. River flow was set to 100 ft^3/s, with approximately 50 ft^3/s diverted into the intake.

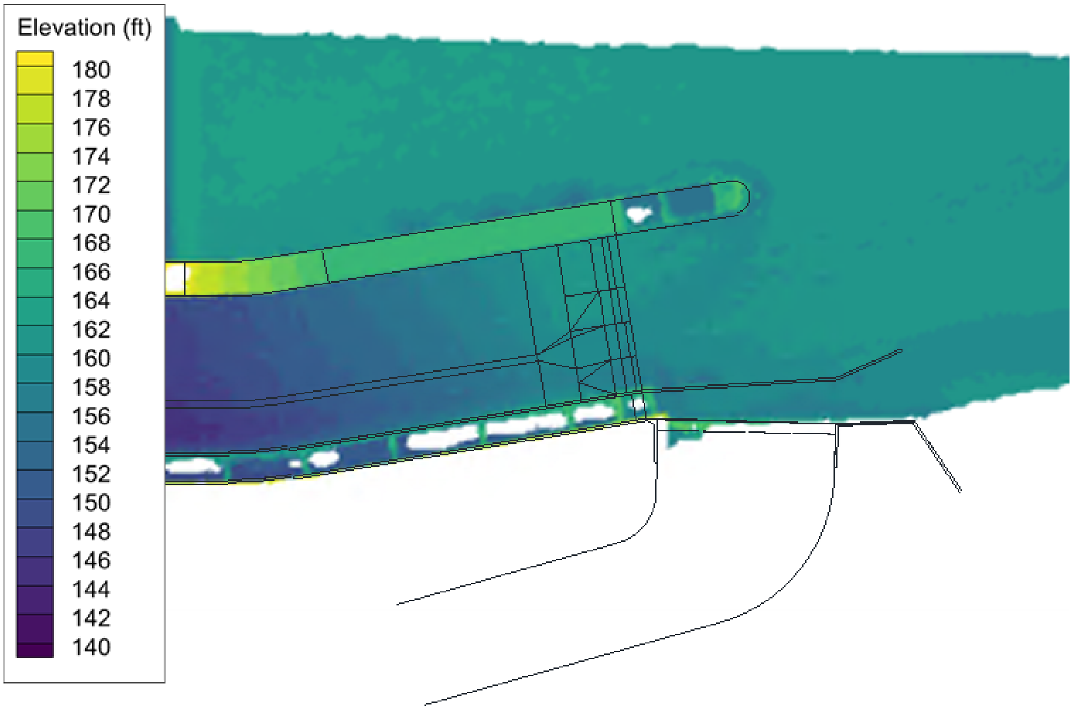


Figure 162. Contour elevation plot of the 1:12 scale castle training wall after 100 ft^3/s.

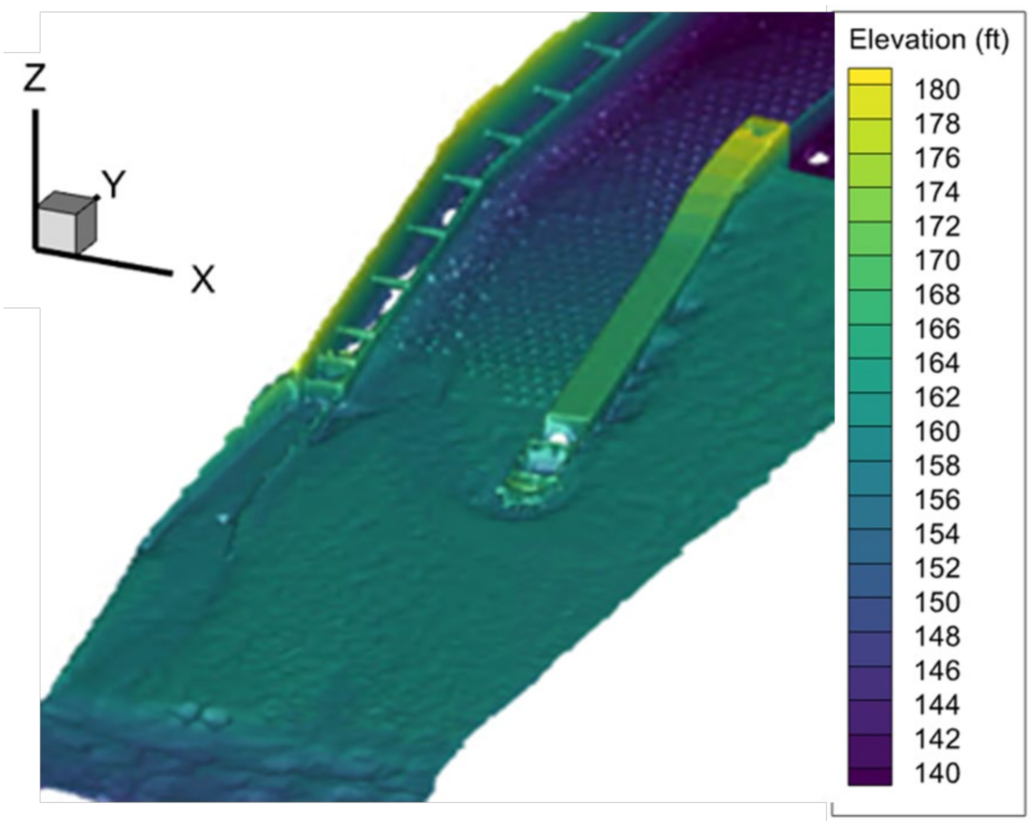


Figure 163. Isometric view of contour elevation plot showing bedforms near the 1:12 scale castle training wall after 100 ft^3/s. Looking downstream.

Conclusions

Physical hydraulic modeling of the Freeman Diversion hardened ramp fish passage alternative was conducted at the Bureau of Reclamation Hydraulics Laboratory in Denver, Colorado. Sediment transport models were constructed and tested at a 1:24 model scale and a 1:12 model scale.

Key findings from both physical models are summarized below.

- Baseline testing of initial designs showed that river flow moved a significant bedform into the area directly upstream of the hardened ramp and canal intake. This bedform primarily consisted of sands and gravels. After the bedform reached a quasi-steady state, sediment continued to transport down the hardened ramp as well as into the canal intake. Several configurations with and without a flushing channel were tested and produced very similar results with the large bedform present and large volumes of sediment ingested into the canal intake. A flushing channel with a training wall was necessary to remove sediment deposited at the apron, canal intake sill, and canal intake gates. Intake configurations without a flushing channel were unable to clear away the sediment deposited on these features.

- Flow conditions at the upstream end of the hardened ramp where fish exit the ramp into the upstream river were greatly improved by moving the river thalweg to the left adjacent to the riverbank. This provided a more uniform flow approaching the hardened ramp. Extending the right wall of the hardened ramp further upstream with a fully rounded bullnose geometry also reduced flow separation and improved hydraulic conditions for fish exiting the ramp, especially for river discharges greater than 1,500 ft^3/s.

- Flow patterns observed at the downstream end of the hardened ramp generally paralleled the topography of the left bank as flow exited the ramp and dispersed uniformly as it moved downstream. Sediment bedforms that developed downstream did not produce extreme localized scour or deposition features that would be detrimental to attracting fish into the ramp. Any deposition in this area due to flushing or sluicing was eventually moved and reformed by continual flow exiting the hardened ramp.

- Modifications to the configuration of rock size and placement in the low flow portion of the hardened ramp provided effective depths and velocities for upstream fish passage for a flow range of 100 ft^3/s to over 500 ft^3/s. Beginning at approximately 300 ft^3/s the baffles began to interact with the flow and provided an effective transition of passageways from the low flow channel into the high flow baffled area as flows increased. For the discharge range of about 500 to 6,000 ft^3/s, the high flow baffled portion of the ramp provided a diversity of depths and velocities within the specified criteria range for effective fish passage (assumed to be depths greater than 1 ft and velocities less than 8 ft/s).

- Several versions of the flushing channel design were tested during the design development phase. The latest version included a “castle” training wall with slots along the top and the apron floor sloping from elevation 154 ft to elevation 146.5 ft at the inlet to the flushing channel (5.2% slope). Results showed that this flushing configuration was effective at removing sediment bed loads from the canal intake and extended for some distance upstream. Additionally, lowering the invert elevation of the flushing channel gate created a larger volume to store sediment on the apron before being ingested into the diversion intake. During flushing, turbulence caused by flow passing through the slots on the top of the wall produced scour on the right side for the along the entire length of the training wall. The hardened ramp remained completely submerged for flushing at river flows greater than 3,000 ft^3/s.

- A desander system was developed to remove sediment within the canal intake before it reached the fish screen bays with the intent to reduce the frequency of using the flushing channel. Three versions of this system were tested in the 1:24 scale model. The last, version 3, showed effective sluicing of sediment back to the river downstream of the hardened ramp. In addition, visual observations indicated that flows through the desander and sluicing culvert were well streamlined with limited shear zones and recirculation and should provide favorable hydraulic conditions for entrained juvenile fish transferred downstream. Effective sluicing of sediments within the sluicing culvert and downstream channel without modulating the flow is limited to tailwater elevations lower than about 145 ft. For tailwater elevations between approximately 145 ft and 147 ft the desander system can still be effectively used if both the sluicing flow rate and sluicing time are increased to help keep the sluice culvert and channel clear of deposited sediments. Clear water (not laden with additional sediments) is needed for this to be effective and was able to be achieved by performing flushing channel operations prior to sluicing with the desander.

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Appendix A: Sediment Modeling Design and Scaling

Summary

Desired model sediment gradations have been determined for the movable bed sections of the Freeman Diversion Dam physical hydraulic models. Prototype gradations within the study reach were reviewed and a target prototype gradation was established. This gradation can be successfully represented at model scale using direct geometric scaling of the coarser material (D_{100} down to D_{50}). Grain sizes for the finer portion of the gradation (D_{40} and smaller) will be increased from geometrically-scaled sizes to better represent the incipient motion and settling velocity characteristics of the prototype materials. Use of alternate-density materials for the models was considered but found unnecessary, so natural quartz-based material will be used for all model sediment. The proposed size adjustments are typical of what has been required in movable bed hydraulic model studies performed by Reclamation's laboratory since the late 1940s and are expected to provide a realistic representation of prototype behavior.

The next steps in model sediment design are to identify potential material sources and determine if a single source can be used or if blending of multiple materials will be needed. Before placing large quantities of sediment in the models we plan to do controlled experiments in a small flume to verify mobility of model sediments at expected velocity and shear stress conditions.

Background

Physical models at 1:24 and 1:12 scales are considered for the study of fish passage alternatives for Freeman Diversion Dam. Two alternative concepts are proposed, a hardened ramp channel and a vertical-slot technical fishway.

Models at both scales will include the left bank at the diversion site, plus a portion of the river channel, but not the full river width. The 1:24 scale models are expected to operate at conditions simulating river discharges from about 5,000 to 226,000 ft^3/s, with actual discharge in the models reduced because the models do not include the full river width. Evaluating some aspects at discharges even lower than 5,000 ft^3/s may be possible. The 1:12 scale models will include a smaller proportion of the river width and will be used to study river discharges from about 150 to 18,900 ft^3/s. Again, discharge within the modeled space will be smaller than the total river discharge for larger river flows since the models will not include the full width of the river channel.

Prototype Sediment

The Freeman Diversion Dam is located on the Santa Clara River in Ventura County, California. The site is an active alluvial channel carrying significant bed and suspended sediment loads. The primary focus of the physical model studies is the transport, deposition, and scour of bed sediments that may impact operation of the fishways, diversion dam, intake structure, and appurtenant features. AECOM (2014) performed field studies (Wolman pebble counts and sediment samples obtained at 1 ft and 5 ft depths in the bed) that provide an estimate of the bed sediment properties within the study reach (at stations 100 to 8,000 ft upstream from the diversion). A summary of the bed sediment gradations obtained from the AECOM study is shown in Figure A-1, with a target prototype gradation to be represented in the model.

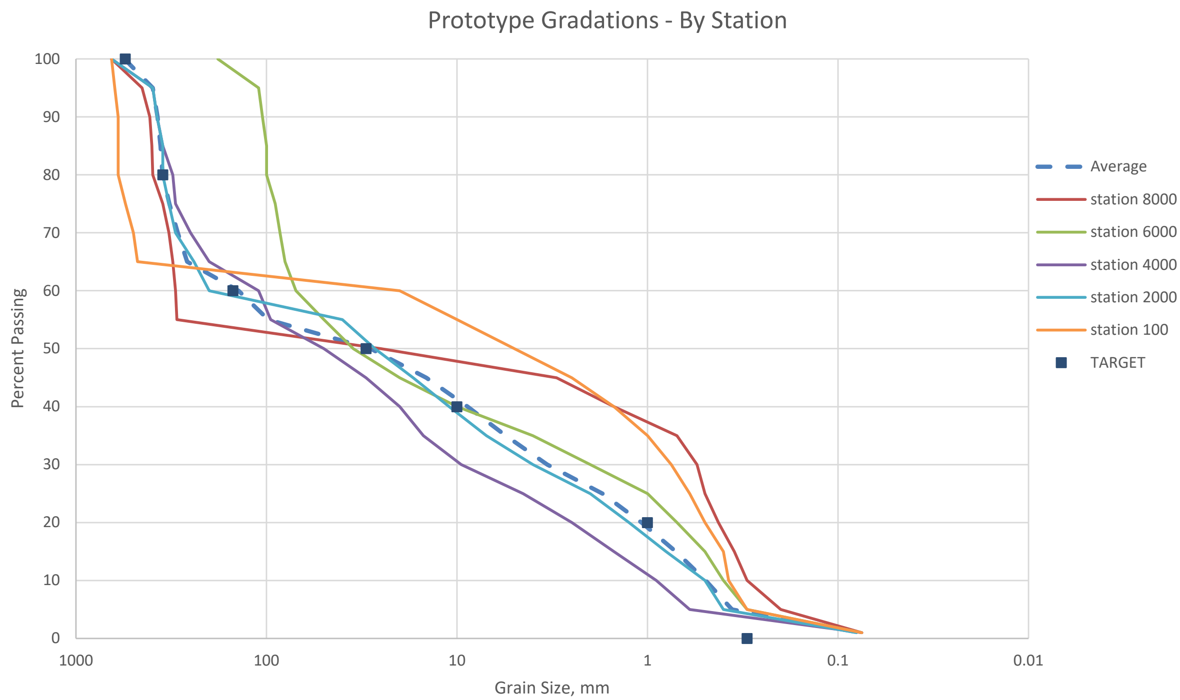

Figure A-1. Prototype sediment gradations.

Sediment Modeling Considerations

The flow of water in a river or canal with a free water surface (open-channel flow) is primarily driven by gravity, and physical models are operated to maintain equal ratios in the model and prototype of the gravitational driving forces and the inertial resistance of the water's mass. Sediment transport is also driven primarily by gravity but is also significantly affected by fluid friction or viscosity. (The flow of water is also affected by viscosity, but usually less so than the fluid transport of sediment). Sediment transport processes cannot be perfectly represented in a physical model because viscosity of the model fluid cannot be adjusted without changing the working fluid of the model, which is impractical or infeasible in most cases. Thus, the influence of viscosity in a model is naturally greater than in a full-scale flow.

Size of sediment particles is the primary characteristic that must be considered when selecting model sediment that will represent prototype sediment behavior in a physical model, but other properties that may require consideration include density, shape (angularity), hardness, and cohesion characteristics (when dealing with fine materials). Density of sediment particles is usually set equal in model and prototype, except when density adjustments might be needed to compensate for other issues (such as the effects of viscosity). Shape is usually not a difficult issue to deal with and is seldom an important consideration with small particles unless one considers using manufactured (synthetic) sediment in a model, which could have a significantly different shape than prototype sediment. For larger particles (gravel and larger), natural sediment sources with a range of angularity are typically available to match the characteristics of prototype stones. Hardness is typically only an issue if the prototype or model materials are quite soft and thus subject to breakdown during transport. Cohesion (caused by interparticle electrostatic forces) is important if the prototype sediment exhibits cohesive characteristics (e.g., silt and clay particles smaller than 0.074 mm or those passing a U.S. No. 200 sieve); if the prototype soil grains are large and exhibit no significant cohesion, then it is important to ensure that model materials will also not exhibit cohesion. Practically, this means avoiding the use of model gradations that contain appreciable amounts of silt or clay particles.

Model Sediment Design

The starting point for the design of model sediment is identifying a desired prototype sediment size to be represented in the model. Figure A-1 shows that the bed sediments within the study area have a broad range of sizes, from about 700 mm to less than 0.1 mm, including boulders, cobbles, gravel, sand, and small amounts of silt and clay (1% or less), and variability at different distances upstream from the diversion. Suspended silt and clay do comprise a significant portion of the total sediment load of the Santa Clara River at times (Williams 1979), but primarily wash through the system and are not present in significant quantities in the riverbed. A target sediment gradation is indicated in Figure A-1 by points plotted at 20 percent increments of the total mass of the bed (percent passing scale) and at the median sediment size, D_{50}. This target was established by judgment, aiming to obtain a relatively smooth gradation curve that represents the average gradation and the stations located in closest proximity to the modeled zone.

The simplest method for converting the desired prototype gradation into a model gradation is geometric scaling, in which the sediment grain sizes are divided by the length scale ratio of the model, either 24 or 12 in the case of the proposed Freeman Diversion Dam models. Table A-1 shows geometric grain sizes calculated for each model scale.

Table A-1. Geometric scaling of sediment sizes.

Percent Passing %	Prototype Grain Size, mm	1:12 Model Grain Size, mm	1:24 Model Grain Size, mm
100	550	46	23
80	350	29	15
60	150	13	6.3
50	30	2.5	1.3
40	10	0.83	0.42
20	1	0.083	0.042
0	0.3	0.025	0.013

To determine if model sediment will behave similarly to prototype sediment, two conditions are checked, incipient motion of bed sediment and the fall velocity of particles in suspension. To first illustrate the concepts of model sediment selection, the geometrically scaled sedimentation gradation for the 1:24 scale model will be considered.

Incipient Motion

The incipient motion check is made using the Shields diagram (Figure A-2), a standardized plot that shows the relation between dimensionless bed shear stress (the Shields parameter, τ_*) and dimensionless grain Reynolds number (R_*) (also called the boundary Reynolds number) at the threshold for bed sediment transport (the Shields Curve). The prototype and model conditions can be plotted for a given sediment size and flow rate. Points that plot above the incipient motion line indicate active bed sediment transport, while those plotting below the line indicate minimal transport. The distance above the incipient motion line is an indicator of the magnitude of the sediment transport rate. With geometrically scaled sediment, the model and prototype Shields parameters (τ_*) are the same, but the grain Reynolds number is reduced in the model in proportion to the length scale ratio raised to the 1.5 power, $R_{*model} = R_{*prototype} / L_r^{1.5}$.

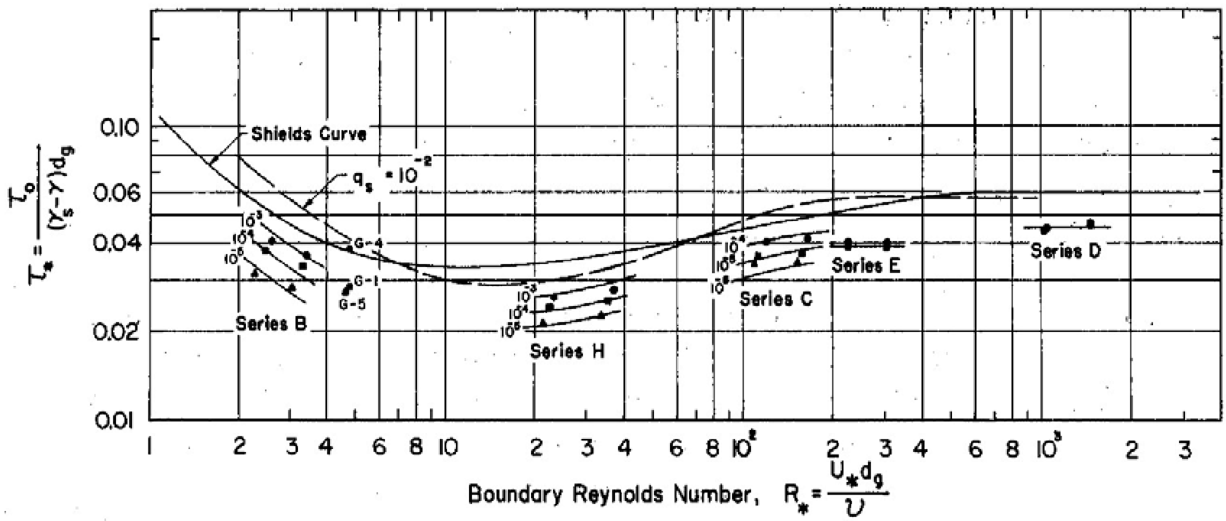

Figure A-2. The Shields diagram for inception of bed sediment transport. The Shields Curve is the incipient motion condition identified by Shields (1936). Lines approximately parallel to the Shields Curve for incipient motion indicate conditions of equal dimensionless sediment transport rate as determined by Taylor (1971).

Figure A-3 shows prototype and 1:24 scale model sediment particles plotted on the Shields diagram for geometrically scaled sediment, *assuming no adjustments of model sediment size or other properties*. (Some adjustments will be needed because geometric scaling of the smallest particles in the prototype gradation would lead to cohesive materials in the model.) The solid data points connected by solid lines are plotted for three representative flow rate conditions, channel unit discharges of approximately 10, 80, and 180 $ft^3/s/ft$, which represent river flow rates of about 6,000, 30,000, and 226,000 ft^3/s. As flow rates increase, data points plot at larger values of R_* and τ_*. The hollow data points connected by dashed lines represent different sediment grain sizes all plotted for the middle flow rate. The sediment sizes shown in the plot are the D_0, D_{20}, D_{40}, D_{50}, and D_{60} sizes shown in Table A-1. The larger sediment sizes have larger R_* values and smaller τ_* values. The D_{80} and D_{100} sediment sizes are well below the incipient motion threshold at these discharges and are thus omitted from the plot. The plotting of these points assumes normal-depth flow conditions, which obviously will not exist in all parts of the model. For example, areas in backwater will experience lower velocity, less shear stress, and less potential for sediment transport.

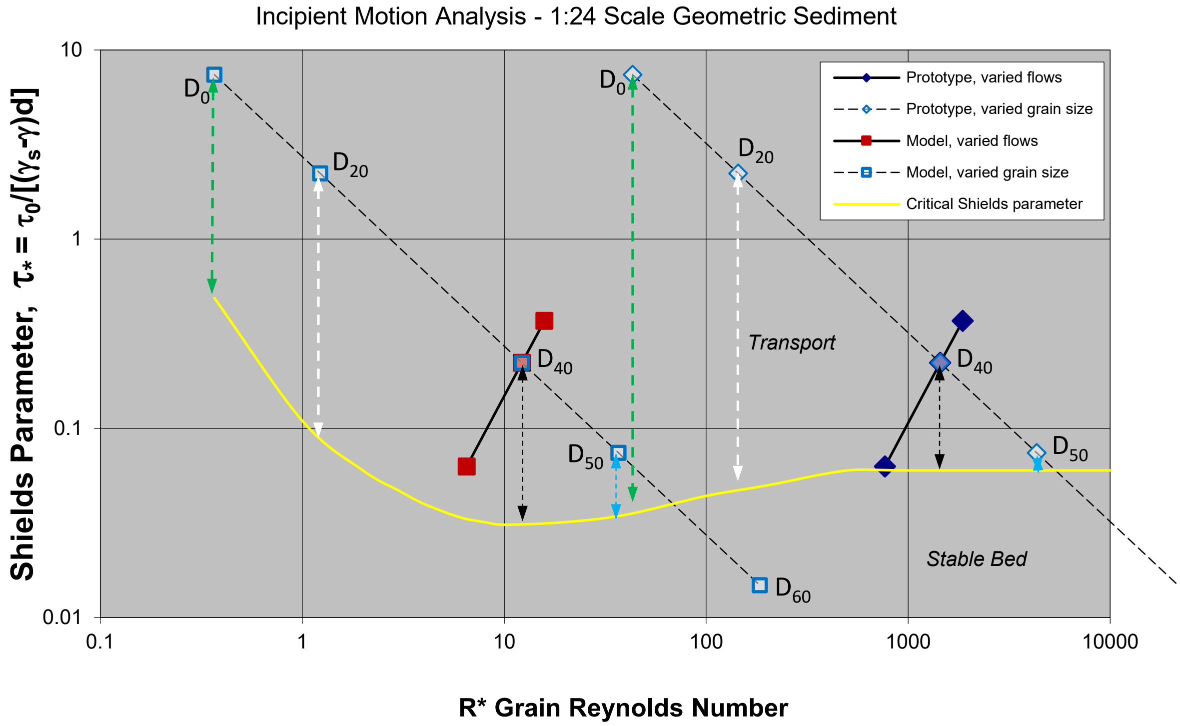

Figure A-3. Shields diagram for 1:24 scale model with geometric sediment scaling.

The key things to note in Figure A-3 are the vertical distances between individually plotted data points and the Critical Shields parameter (incipient motion) curve. When corresponding prototype and model points plot at similar distances above the line, similar dimensionless sediment transport rates can be expected in the model. The nonlinearity of the Shields curve prevents the transport of most sediment sizes from being perfectly matched. For example, the transport of the smallest sediment grains (D_0 to D_{20}) is underrepresented in the model compared to the prototype (although model and prototype both plot far above the curve and are thus very actively transported at the depicted flow conditions). Transport of D_{40} and D_{50} sizes is somewhat overrepresented in the model (model points plot farther above the incipient motion curve than their associated prototype points). A particle somewhere between the D_{20} and D_{40} sizes will plot at equal distances above the incipient motion curve. This could be described as the "sweet spot" with the most accurate bed transport modeling.

Settling Velocity

To evaluate the behavior of suspended sediment in the model (which could include bed sediment that is briefly in suspension in more turbulent flow zones), the settling velocity of prototype and model particles is considered. The objective is for the model sediment grains to settle with a velocity that is reduced from the prototype in proportion to the square root of the model length scale ratio. This keeps the settling velocity in proportion to other flow velocities of the model and produces a similar depth-wise distribution of suspended sediment concentrations in the model and prototype.

Assuming quartz-based sediment in the model and prototype, Figure A-4 graphically shows settling velocities for the geometrically scaled key grain sizes considered earlier (D_0 to D_{60}). Blue circles indicate prototype settling velocities and black construction lines illustrate scaling of grain sizes and their associated settling velocities. The solid lines with arrows illustrate the scaling of a 30-mm diameter prototype particle. The prototype settling velocity is about 60 cm/s. Dividing the grain size by 24 yields a 1.25 mm diameter and a settling velocity of about 12.3 cm/s, which lands on the line indicating settling velocity proportional to sqrt(*d*), so no adjustment of scaled grain size is needed. The settling velocity has been reduced by a factor of $24^{0.5} = 4.9$. Similar results occur for larger grain sizes (construction lines not shown). For smaller particles (dashed lines and red construction lines), curvature of the settling velocity relation requires an increased sediment grain size. For example, the D_0 particle (0.3 mm diameter) would be geometrically scaled to 0.013 mm with a settling velocity of about 0.02 cm/s (a 15-fold reduction). For a correctly scaled settling velocity, the grain size must be increased to about 0.1 mm.

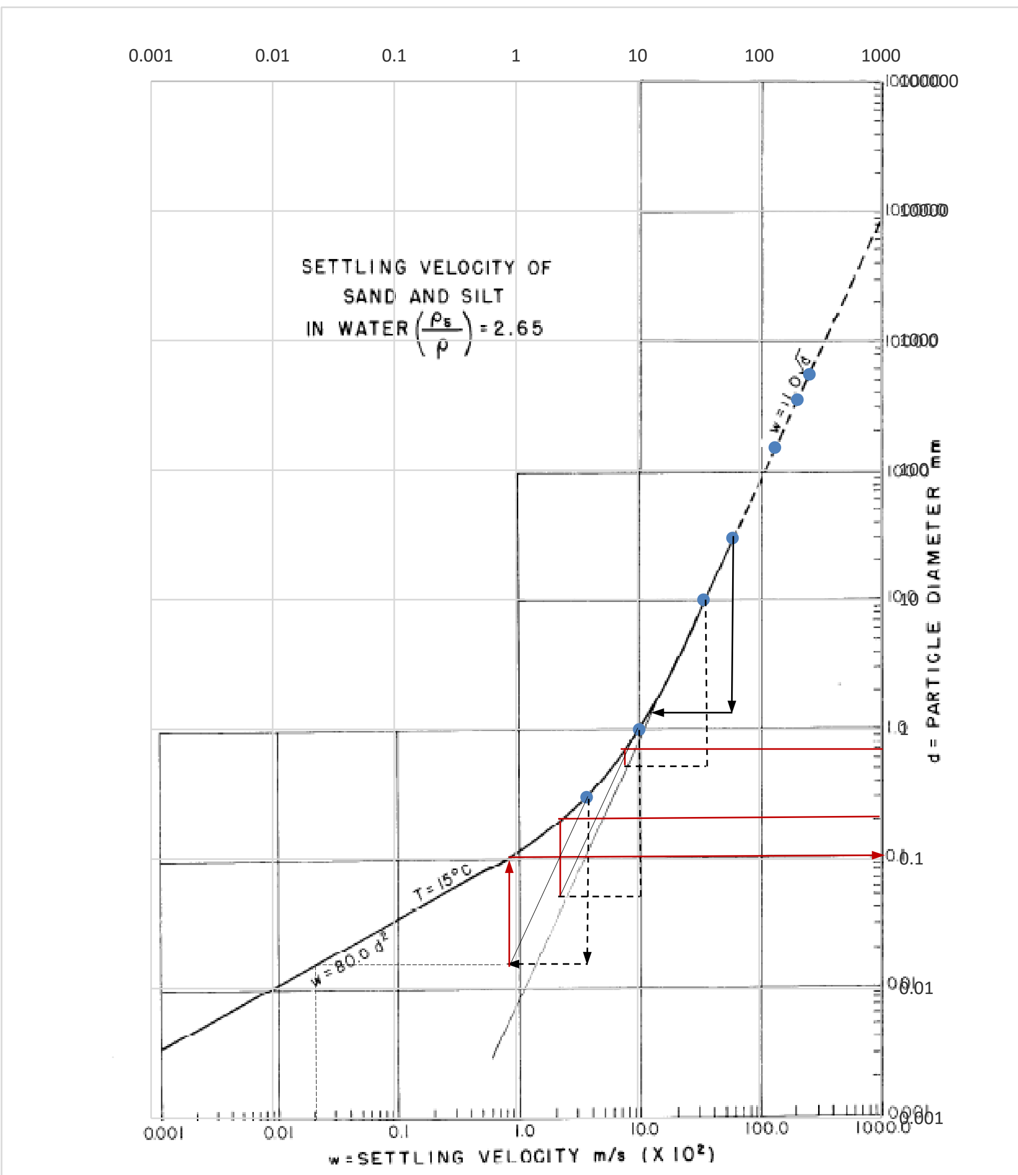

Figure A-4. Settling velocity of prototype and model sediment grains. The horizontal axis units are equivalent to cm/s.

Figure A-4 shows that the use of geometrically scaled sediment would lead to settling velocities that are too small for grain sizes at the small end of the gradation. These sediment particle sizes must be increased in the model to obtain correct settling velocities. A second consideration is the fact that model sediment particles must be kept larger than the U.S. No. 200 sieve size (0.075 mm) to avoid the potential for cohesive behavior in the model.

Model Sediment Gradations

Table A-2 shows model sediment gradations adjusted to produce correct settling velocities. All proposed model sediment is larger than 0.074 mm. Figures A-5 and A-6 show the incipient motion analysis for these proposed sediment sizes.

Table A-2. Adjusted model sediment sizes. Grain sizes highlighted in bold are increased compared to geometric scaling.

Percent Passing %	Prototype Grain Size, mm	1:12 Model Grain Size, mm	1:24 Model Grain Size, mm
100	550	46	23
80	350	29	15
60	150	13	6.3
50	30	2.5	1.3
40	10	**1.0**	**0.65**
20	1	**0.24**	**0.2**
0	0.3	**0.12**	**0.1**

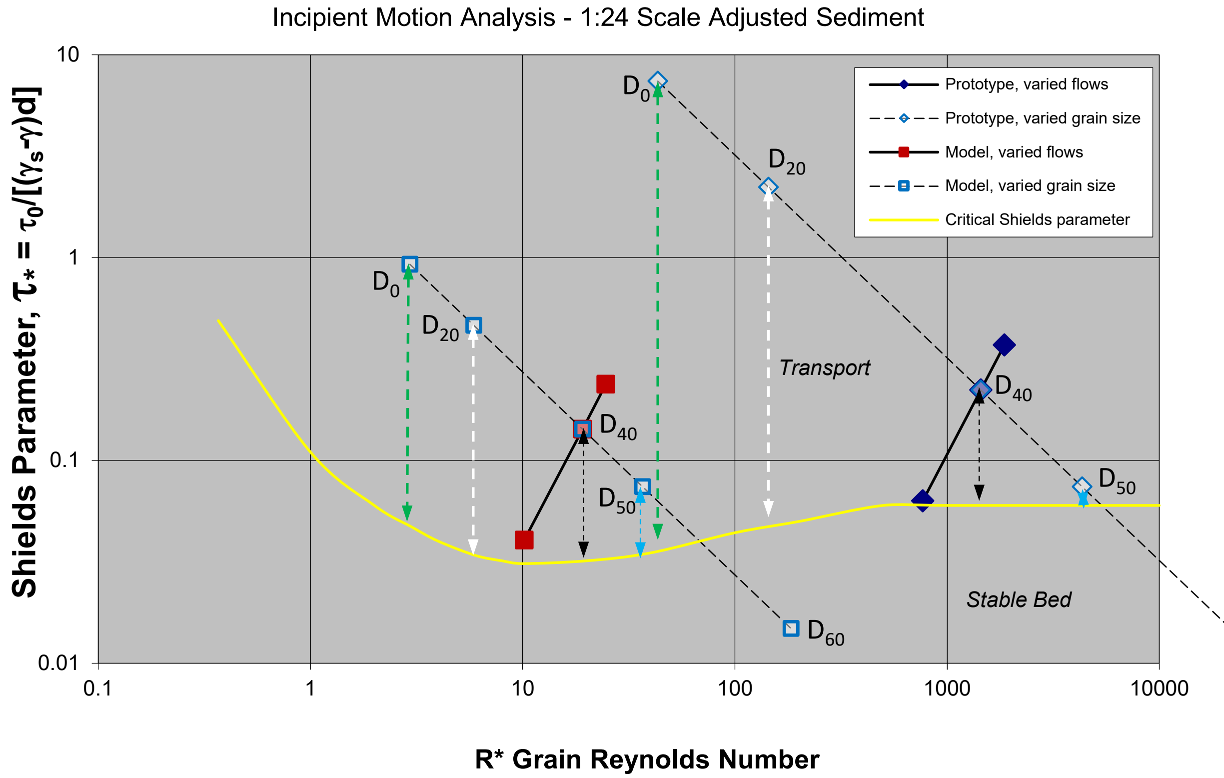

Figure A-5. Shields diagram for adjusted 1:24 scale sediment.

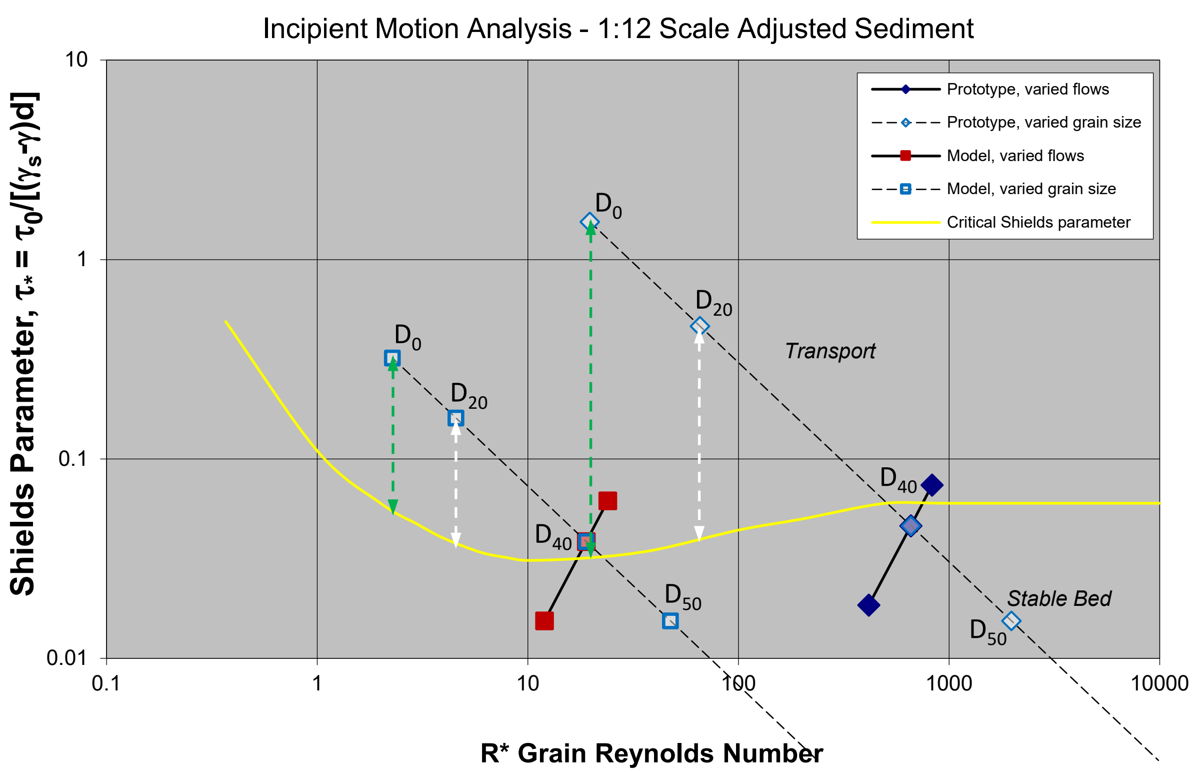

Figure A-6. Shields diagram for adjusted 1:12 scale sediment at river discharges up to about 10,000 ft^3/s.

For the 1:24 scale, Figure A-5 shows that there is still some tendency for underrepresentation of sediment transport rates for the D_0 to D_{20} range. The “sweet spot” for optimum modeling of transport rates appears to just below D_{40}. There is little opportunity to improve the D_0 to D_{20} range, since the slope of the Shields curve approximately matches the slope of the curve that describes the changes in τ_* and R_* with changing sediment size. Adjusting sediment sizes shifts the model points right or left, but due to the slope of the two lines/curves, little change can be achieved. In Figure A-6 (1:12 scale model) the best sediment transport modeling is in the D_{20} to D_{40} range. A little more adjustment (increased sediment size) of the D_{40} point could optimize bed transport modeling for that sediment size, but at the cost of a poorer match of the modeled settling velocity. The D_0 to D_{20} range might be improved slightly by reducing the sediment size (sliding points up and to the left along the diagonal dashed line), but again this would affect the settling velocity modeling and has only limited benefit due to the shape of the critical Shields parameter curve. There is also limited range for reducing the sediment size before the cohesive-sediment grain size limit is reached. Other adjustments that are often considered for sediment modeling include the use of low-density materials such as coal, walnut shells, plastics, and acrylics, scale distortion (use of differing horizontal and vertical scale ratios), and slope distortion or discharge adjustments. Adjustments affect every size of sediment in the model (low-density materials are not typically used for only a part of a gradation, especially when the gradation must be broad; 1- to 2-inch gravel down to fine sand in this case), and each adjustment often requires further compensation, so the justification for making additional adjustments must be strong. In this case, natural sediment with the minor size adjustments described for the finer parts of the gradation should provide effective model performance.

Figure A-7 shows target model sediment gradation curves (i.e., gradations in Table A-2). Sources of potential sediment will be investigated to determine if a single source can be used or if sediment blending will be needed (combining sand and gravel products).

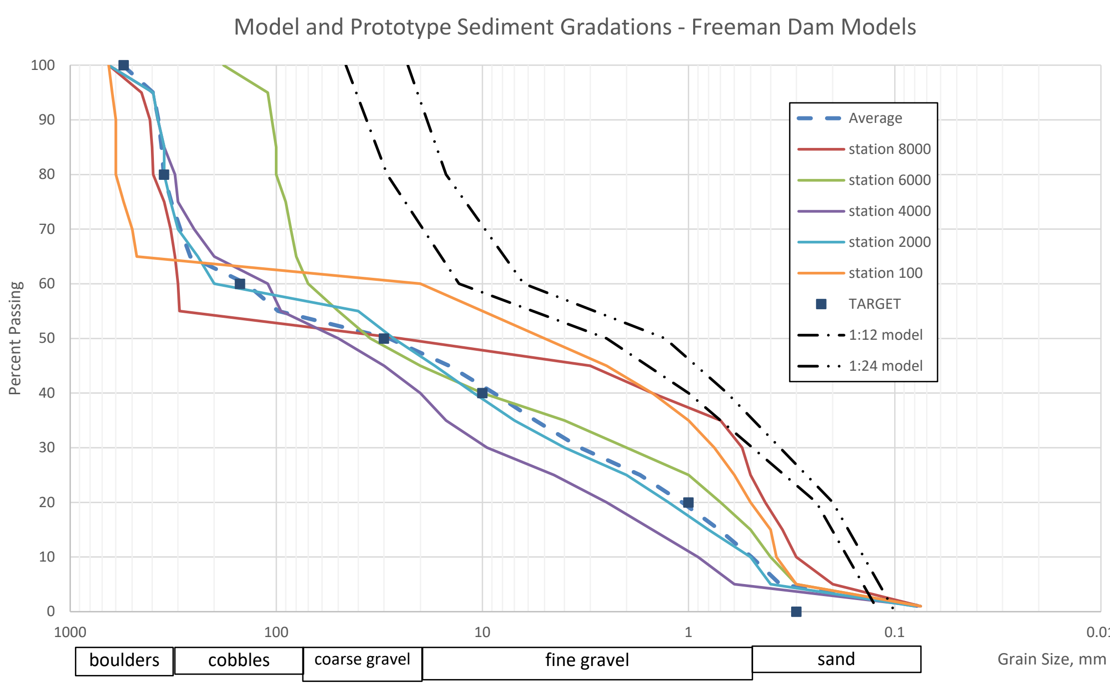

Figure A-7. Model and prototype sediment gradations.

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Appendix B: Summary of 1:24 Scale Baseline Results

Test Results and Observations for MOD-6 and MOD-9 Design Configurations

For each of the tested flow rates, general model observations are summarized. Accompanying figures that support the text descriptions are provided following each narrative section. Contour elevation plots and photographs are included to compare post-test bed topography for MOD-6 and MOD-9 designs. Color maps of LSPIV-derived prototype surface velocity magnitudes in the key area upstream of the diversion entrance and hardened ramp for the MOD-6 and MOD-9 designs are displayed. Tabular data of average prototype surface velocity magnitudes at the diversion intake control gates and at the hardened ramp exit are shown.

Detailed model observations for flushing channel closed, open, and removed at each river flow with the MOD-6 and MOD-9 designs are provided in Appendix B-1. Contour elevation difference maps between pre- and post-test conditions for MOD-6 and MOD-9 designs are shown in Appendix B-2.

Average water surface elevation measurements are shown in Table B-1 and Table B-2, and flow split data between the canal diversion, dam overflow, and hardened ramp are shown in Table B-3 and Table B-4.

Table B-1. Average water surface elevations for each tested flow condition for the MOD-6 configuration.

River Flow Rate (ft^3/s)	Upstream Channel (ft)	Upstream Intake (ft)	Downstream Intake (ft)	Dam Crest-Left (ft)	Dam Crest-Right (ft)	Tailwater (ft)
3,000 (flushing closed)	161.92	160.29	158.64	161.37	N/A	144.83
3,000 (flushing open)	161.81	159.94	158.34	161.52	N/A	145.19
3,000 (flushing removed)	162.21	160.10	158.92	161.71	N/A	145.48
6,000 (flushing closed)	162.81	161.94	160.63	162.61	161.24	145.71
6,000 (flushing open)	162.51	161.89	161.61	162.13	161.04	145.57
6,000 (flushing removed)	162.76	161.23	159.99	162.85	161.42	145.89
12,000 (flushing closed)	164.46	164.61	164.80	163.64	162.44	148.63
12,000 (flushing opened)	164.23	164.00	164.03	163.75	162.18	149.07
12,000 (flushing removed)	164.08	164.05	164.06	164.44	162.95	150.02
30,000 (flushing closed)	167.36	168.03	168.27	166.45	165.48	155.42
30,000 (flushing opened)	167.07	167.31	167.60	166.06	165.16	154.87
30,000 (flushing removed)	166.65	167.29	167.40	166.55	165.73	154.92

Table B-2. Average water surface elevations for each tested flow condition for the MOD-9 configuration.

River Flow Rate (ft^3/s)	Upstream Channel (ft)	Upstream Intake (ft)	Downstream Intake (ft)	Dam Crest-Left (ft)	Dam Crest-Right (ft)	Tailwater (ft)
3,000 (flushing closed)	162.21	162.32	161.93	162.22	N/A	144.26
3,000 (flushing open)	161.90	161.44	158.07	161.89	N/A	143.82
3,000 (flushing removed)	162.39	161.96	160.87	162.39	162.04	144.50
6,000 (flushing closed)	163.91	163.66	162.90	163.64	163.07	145.12
6,000 (flushing open)	163.31	163.04	161.58	163.41	162.84	144.77
6,000 (flushing removed)	163.75	163.49	162.47	163.59	163.21	145.31
12,000 (Flushing closed)	165.05	165.74	165.79	164.77	164.54	150.36
12,000 (flushing opened)	164.29	164.86	164.83	163.99	164.35	149.83
12,000 (flushing removed)	164.72	165.43	165.43	164.31	164.67	150.03
30,000 (flushing closed)	167.60	168.60	168.61	167.16	167.37	155.10
30,000 (flushing opened)	167.39	168.19	168.29	167.22	166.87	155.07
30,000 (flushing removed)	167.46	168.34	168.45	167.27	167.08	155.42

Table B-3. Flow split data between the canal diversion, dam overflow, and hardened ramp for the MOD-6 configuration.

River Flow Rate (ft^3/s)	Measured Model River Flow Rate (ft^3/s)	Canal Diversion Flow Rate (ft^3/s)	Dam Flow Rate (ft^3/s)	Hardened Ramp Flow Rate (ft^3/s)
3,000 (flushing closed)	3,063	828	625	1,610
3,000 (flushing open)	3,106	587	803	1,716
3,000 (flushing removed)	3,155	813	1,066	1,277
6,000 (flushing closed)	6,097	1,012	2,678	2,407
6,000 (flushing open)	6,045	769	1,797	3,479
6,000 (flushing removed)	6,055	1,005	3,254	1,796
12,000 (flushing closed)	12,010	0	5,939	6,072
12,000 (flushing opened)	12,121	0	5,702	6,419
12,000 (flushing removed)	12,074	0	8,117	3,958
30,000 (flushing closed)	29,986	0	17,172	12,814
30,000 (flushing opened)	29,683	0	15,598	14,084
30,000 (flushing removed)	29,787	0	17,967	11,820

Table B-4. Flow split data between the canal diversion, dam overflow, and hardened ramp for the MOD-9 configuration.

River Flow Rate (ft^3/s)	Measured Model River Flow Rate (ft^3/s)	Canal Diversion Flow Rate (ft^3/s)	Dam Flow Rate (ft^3/s)	Hardened Ramp Flow Rate (ft^3/s)
3,000 (flushing closed)	3,099	874	125	2,099
3,000 (flushing open)	3,114	580	138	2,394
3,000 (flushing removed)	3,021	883	534	1,604
6,000 (flushing closed)	6,226	923	2,506	2,797
6,000 (flushing open)	6,100	521	1,915	3,663
6,000 (flushing removed)	6,105	742	2,359	3,004
12,000 (flushing closed)	12,125	0	5,915	6,210
12,000 (flushing opened)	12,161	0	5,554	6,606
12,000 (flushing removed)	12,042	0	6,603	5,439
30,000 (flushing closed)	29,875	0	17,376	12,499
30,000 (flushing opened)	29,867	0	16,393	13,474
30,000 (flushing removed)	29,903	0	16,966	12,937

River Flow 3,000 ft^3/s

MOD-6 Flushing Channel Closed

At 3,000 ft^3/s, the majority of flow stayed within the main low-flow river channel approaching the hardened ramp and diversion intake. As it was dependent on the geometry of the channel, the flow curved left as it approached the hardened ramp and diversion causing a significant shear zone off the bull nose on the right wall of the ramp. Coarse and fine sands moved down the main channel as a bed form which deposited in front of the intake gates and upstream end of the hardened ramp.

At the downstream end of the hardened ramp, the main flow path followed the left bank, leaving sand bars on the left over the hardened topography of the bank as well as on the right. The baffles on the right side of the ramp were inundated with sand for the downstream 25% of the ramp. Little sediment deposition occurred within the low flow section of the ramp and there was a slight depression downstream from the ramp with no scour.

MOD-6 Flushing Channel Open

When the flushing channel was initially opened, sediment near the leading edge of the flushing channel wall and downstream end of gate 4 of the diversion intake was quickly flushed downstream. The zone of influence for flushing was approximately one flushing channel width upstream (15 ft). Sediment deposited on the apron in front of the diversion gates was not mobilized during the 2-hour test duration.

On the downstream end of the hardened ramp, scour developed where the flushing flow exited the channel. The reverse roller carried sediment back against the flushing channel and the depth of the scour hole was not significant. Sand bars on both left and right sides shifted towards the left due to the energy of the flushing flow exiting the channel.

MOD-6 Flushing Channel Removed

Without the flushing channel, flow inundated part of the left and right floodplain at elevation 162 ft. Coarse and fine sands moved down the main low-flow river channel as a bed form which deposited in front of the right two intake gates (gates 3-4) and upstream end of the hardened ramp. During the test duration, no sediment deposition was observed in front of the left two intake gates (gates 1-2), with both the sill and the apron remaining relatively free of sediment.

On the downstream end of the hardened ramp, no significant scour was observed. The baffles on the right side of the ramp were inundated with sand for the downstream 25% of the ramp, and no sediment accumulated in the low flow section of the ramp.

MOD-9 Flushing Channel Closed

At 3,000 ft^3/s, the approach flow was more distributed from the main low-flow river channel to the left bank, inundating the left bank depositional area of elevation 162 ft. Flow over the dam crest was almost exclusively over the left notch portion. Little sediment accumulated upstream of the hardened ramp and intake gates.

On the downstream end of the hardened ramp, the baffles on the right side of the ramp were inundated with sediment for approximately the 30% downstream portion of the ramp with little flow movement along the right ramp wall. Some scour was observed downstream of the low flow channel with the scour pattern continuing to the end of the model extents.

MOD-9 Flushing Channel Open

After the flushing channel was opened, sediment deposition shifted from in front of the hardened ramp to more concentrated in front of the flushing channel. As there was little sediment accumulation in front of the intake gates, the area in front of the gates remained clear with little impact from the flushing channel.

On the downstream end of the hardened ramp, the scour pattern shifted to downstream of the flushing channel.

MOD-9 Flushing Channel Removed

Without the flushing channel, flow inundated part of the right depositional area at elevation 162 ft and part of the left depositional area at elevation 162 ft and 164 ft. As more of the right bank was active with flow, more flow was diverted over the dam crest. Sediment moved from the upstream channel and evenly deposited immediately upstream of the hardened ramp and in front of the low flow channel. The area in front of the intake remained clear of sediment.

On the downstream end of the hardened ramp, nearly a third of the baffles were fully covered by sediment. The invert of the low flow section was also covered by sediment.

Figure B-1. View looking downstream after dewatering for MOD-6 design with flushing channel closed at 3,000 ft^3/s.

Figure B-2. View looking upstream for MOD-6 design with flushing channel closed after 3,000 ft^3/s flow rate.

Figure B-3. View looking downstream after dewatering for MOD-9 design with flushing channel closed at 3,000 ft^3/s.

Figure B-4. View looking upstream for MOD-9 design with flushing channel closed after 3,000 ft^3/s flow rate.

Figure B-5. View looking downstream after dewatering for MOD-6 design with flushing channel open at 3,000 ft^3/s.

Figure B-6. View looking upstream for MOD-6 design with flushing channel open after 3,000 ft^3/s flow rate.

Figure B-7. View looking downstream after dewatering for MOD-9 design with flushing channel open at 3,000 ft^3/s.

Figure B-8. View looking upstream for MOD-9 design with flushing channel open after 3,000 ft^3/s flow rate.

Figure B-9. View looking downstream after dewatering for MOD-6 design with flushing channel removed at 3,000 ft^3/s.

Figure B-10. View looking upstream for MOD-6 design with flushing channel removed after 3,000 ft^3/s flow rate.

Figure B-11. View looking downstream after dewatering for MOD-9 design with flushing channel removed at 3,000 ft^3/s.

Figure B-12. View looking upstream for MOD-9 design with flushing channel removed after 3,000 ft^3/s flow rate.

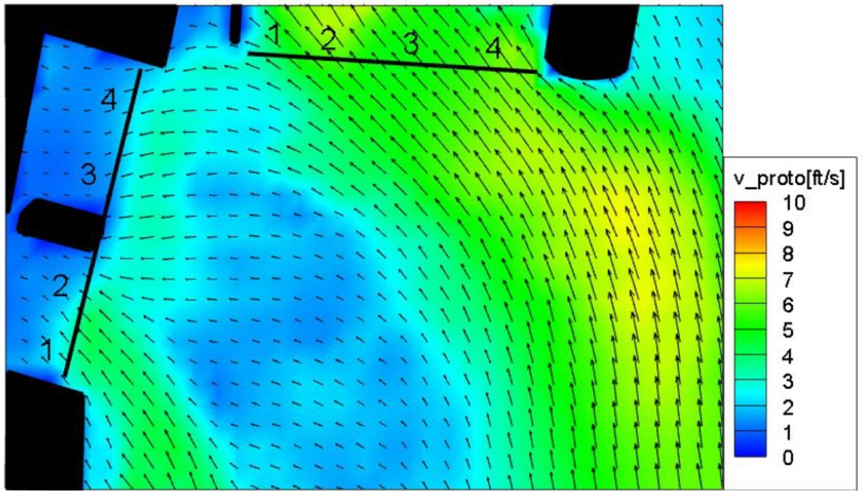

Figure B-13. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-6 design with flushing channel closed at 3,000 ft^3/s river flow.

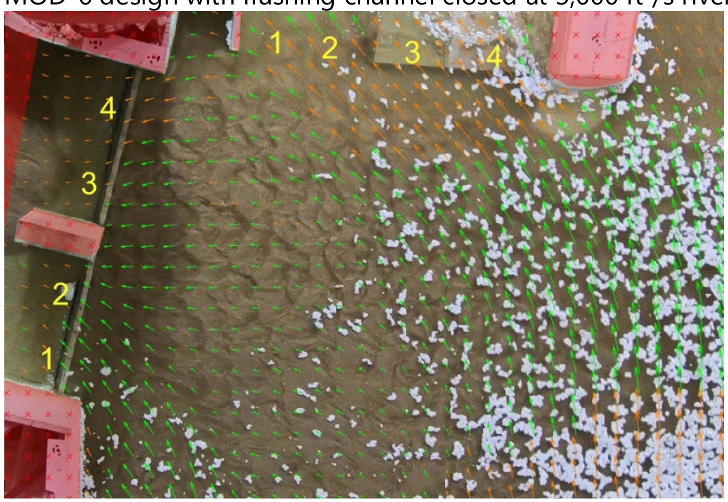

Figure B-14. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-6 design with flushing channel closed at 3,000 ft^3/s river flow.

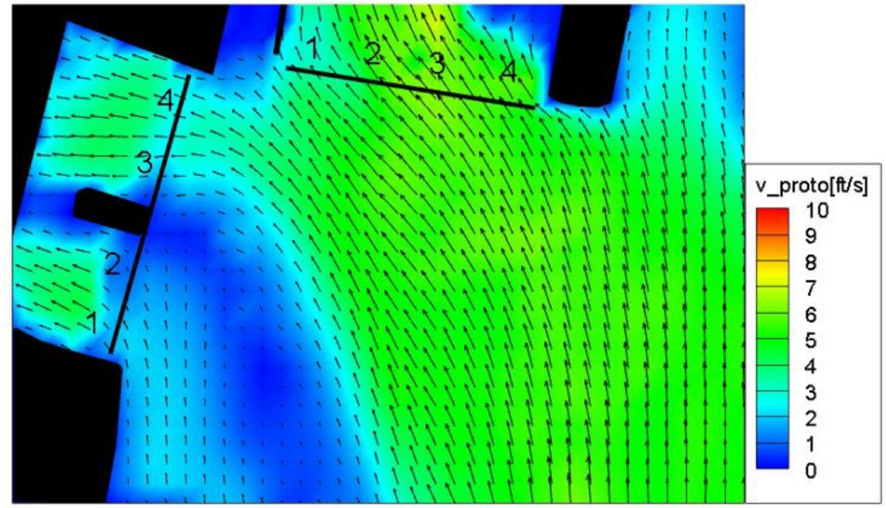

Figure B-15. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-9 design with flushing channel closed at 3,000 ft^3/s river flow.

Figure B-16. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-9 design with flushing channel closed at 3,000 ft^3/s river flow.

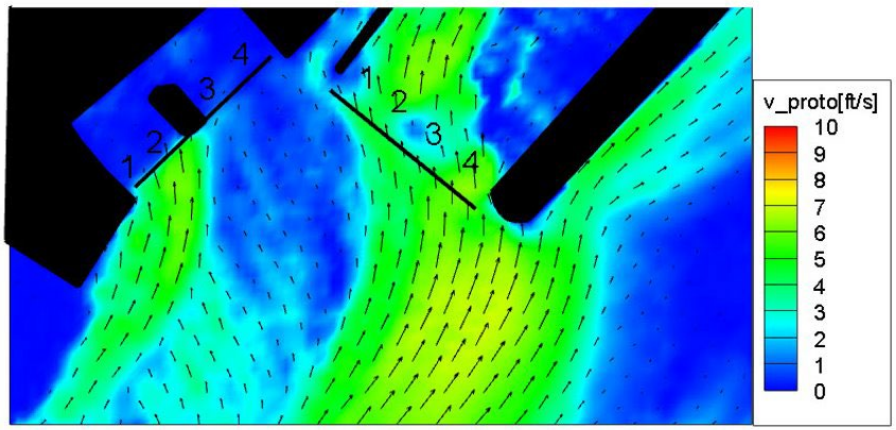

Figure B-17. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-6 design with flushing channel open at 3,000 ft^3/s river flow.

Figure B-18. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-6 design with flushing channel open at 3,000 ft^3/s river flow.

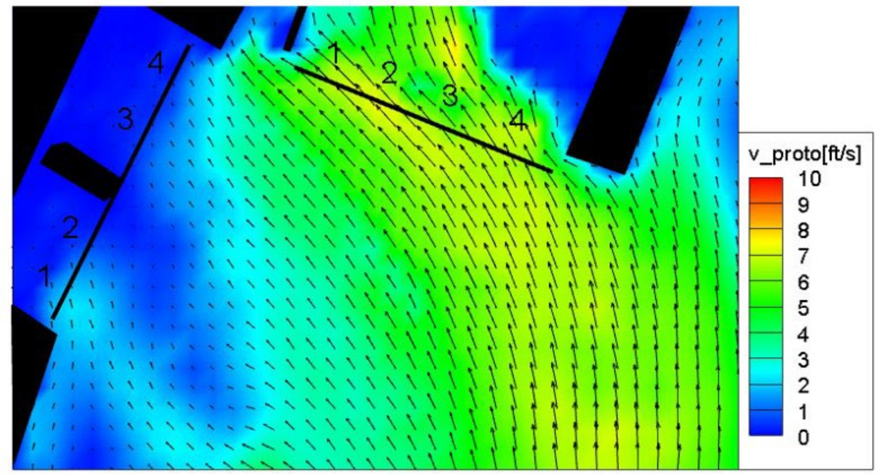

Figure B-19. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-9 design with flushing channel open at 3,000 ft^3/s river flow.

Figure B-20. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-9 design with flushing channel closed at 3,000 ft^3/s river flow.

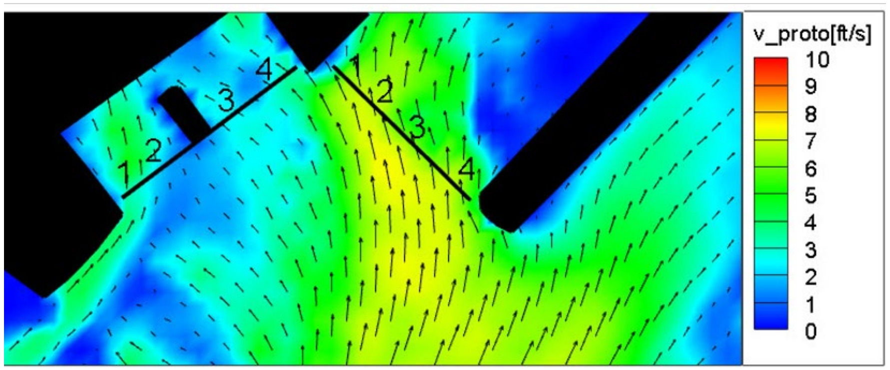

Figure B-21. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-6 design with flushing channel removed at 3,000 ft^3/s river flow.

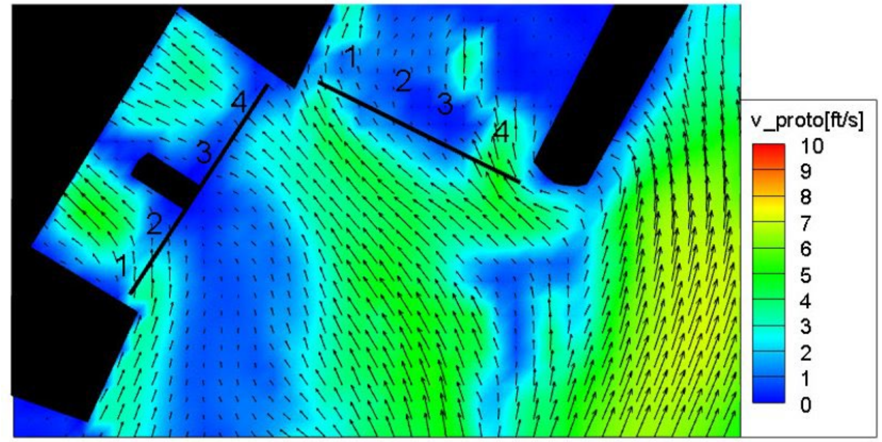

Figure B-23. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-9 design with flushing channel removed at 3,000 ft^3/s river flow.

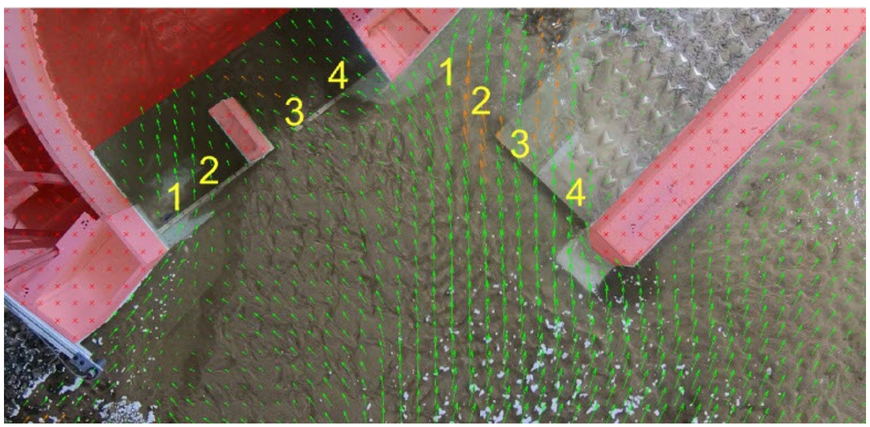

Figure B-22. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-6 design with flushing channel removed at 3,000 ft^3/s river flow.

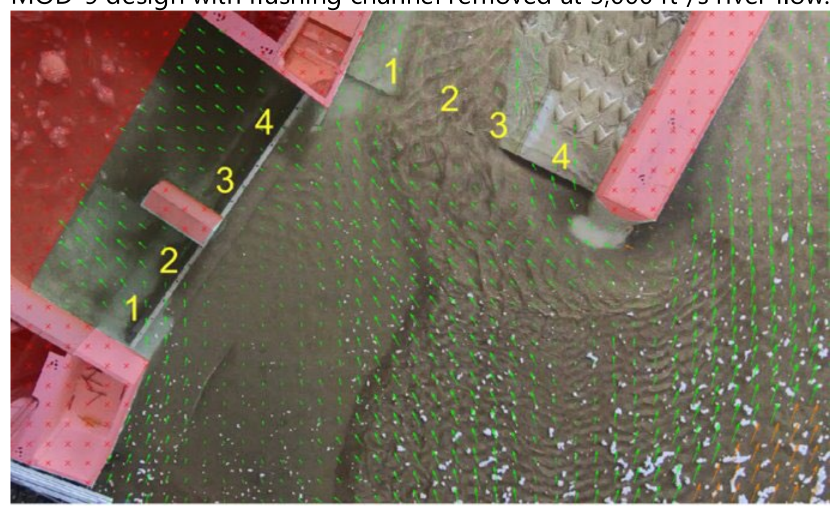

Figure B-24. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-9 design with flushing channel removed at 3,000 ft^3/s river flow.

Table B-5. Average prototype surface velocity magnitudes from LSPIV data at the diversion intake gates at 3,000 ft^3/s. Point "A" and "B" signify the left and right half of the gate, respectively.

	MOD-6 Average Prototype Surface Velocity Magnitude at Diversion Intake Gates (ft/s)			**MOD-9 Average Prototype Surface Velocity Magnitude at Diversion Intake Gates (ft/s)**		
Location	**Flushing Channel Closed**	**Flushing Channel Open**	**Flushing Channel Removed**	**Flushing Channel Closed**	**Flushing Channel Open**	**Flushing Channel Removed**
Gate 1A	2.3	2.3	2.6	1.3	1.7	2.3
Gate 1B	3.3	2.2	2.9	1.7	1.8	2.7
Gate 2A	3.0	3.2	1.7	1.2	0.8	1.3
Gate 2B	1.7	2.8	1.1	0.7	0.2	0.3
Gate 3A	1.5	1.1	2.6	1.6	0.6	0.5
Gate 3B	2.0	0.4	1.8	2.5	0.5	1.0
Gate 4A	2.2	0.1	2.8	2.6	0.4	1.0
Gate 4B	1.8	0.3	2.4	2.1	0.4	0.5

Table B-6. Average prototype surface velocity magnitudes from LSPIV data at hardened ramp exit at 3,000 ft^3/s. Point "A" and "B" signify the left and right half of the gate, respectively.

	MOD-6 Average Prototype Surface Velocity Magnitude at Hardened Ramp Exit (ft/s)			**MOD-9 Average Prototype Surface Velocity Magnitude at Hardened Ramp Exit (ft/s)**		
Location	**Flushing Channel Closed**	**Flushing Channel Open**	**Flushing Channel Removed**	**Flushing Channel Closed**	**Flushing Channel Open**	**Flushing Channel Removed**
Gate 1A	2.9	1.9	2.2	2.8	3.9	2.0
Gate 1B	4.5	3.8	6.7	3.4	6.7	2.0
Gate 2A	5.6	4.5	6.9	4.0	7.1	1.3
Gate 2B	5.0	4.0	6.2	5.9	6.7	0.9
Gate 3A	4.9	3.6	6.2	6.2	6.5	0.9
Gate 3B	5.3	4.7	6.1	5.9	6.6	1.5
Gate 4A	5.9	6.1	6.9	5.6	6.7	4.2
Gate 4B	5.0	5.6	5.3	4.3	5.6	3.1

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

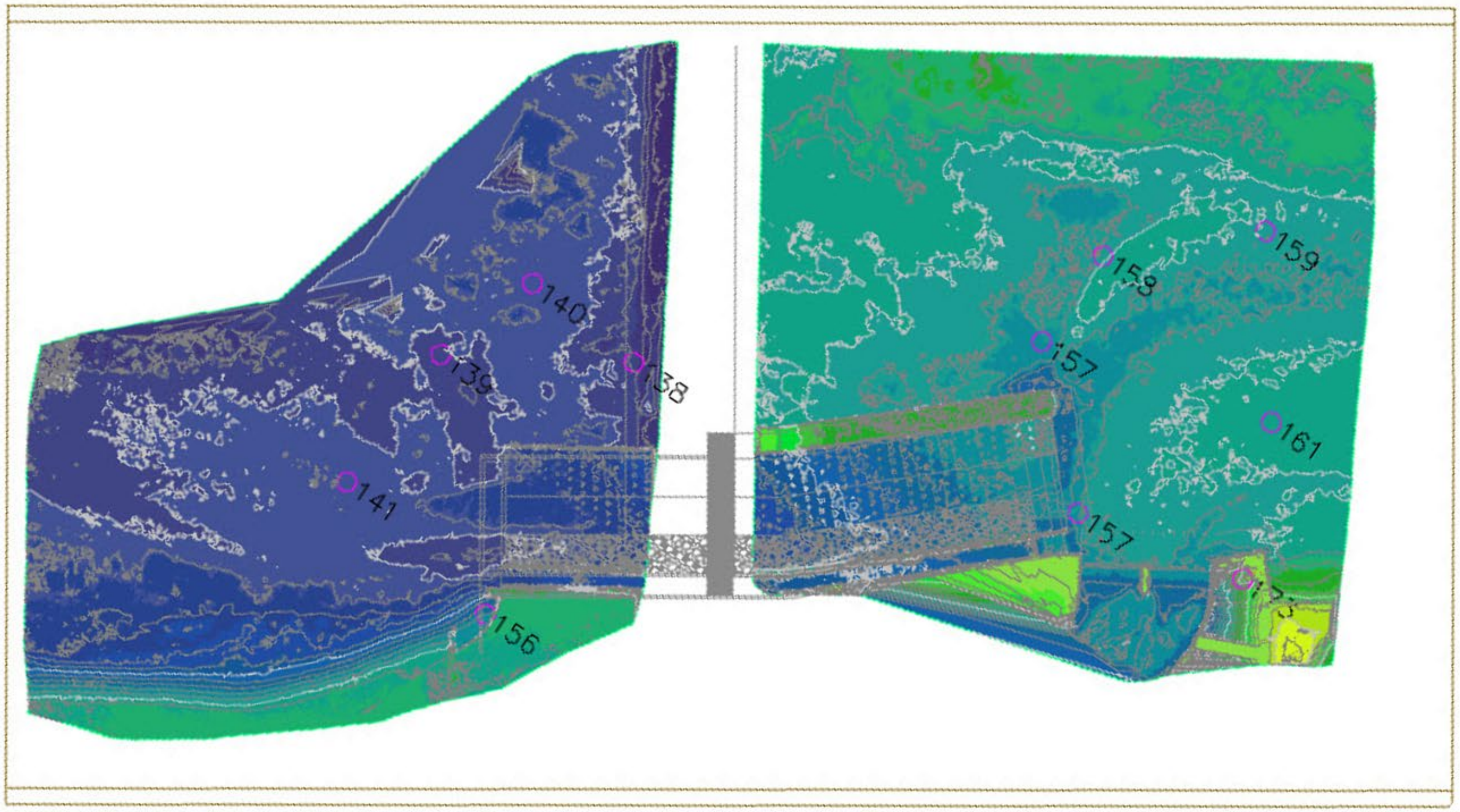

Figure B-25. Elevation contours after model run for MOD-6 design with flushing channel closed at 3,000 ft^3/s river flow. Flow is from right to left.

Elevations Table

Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

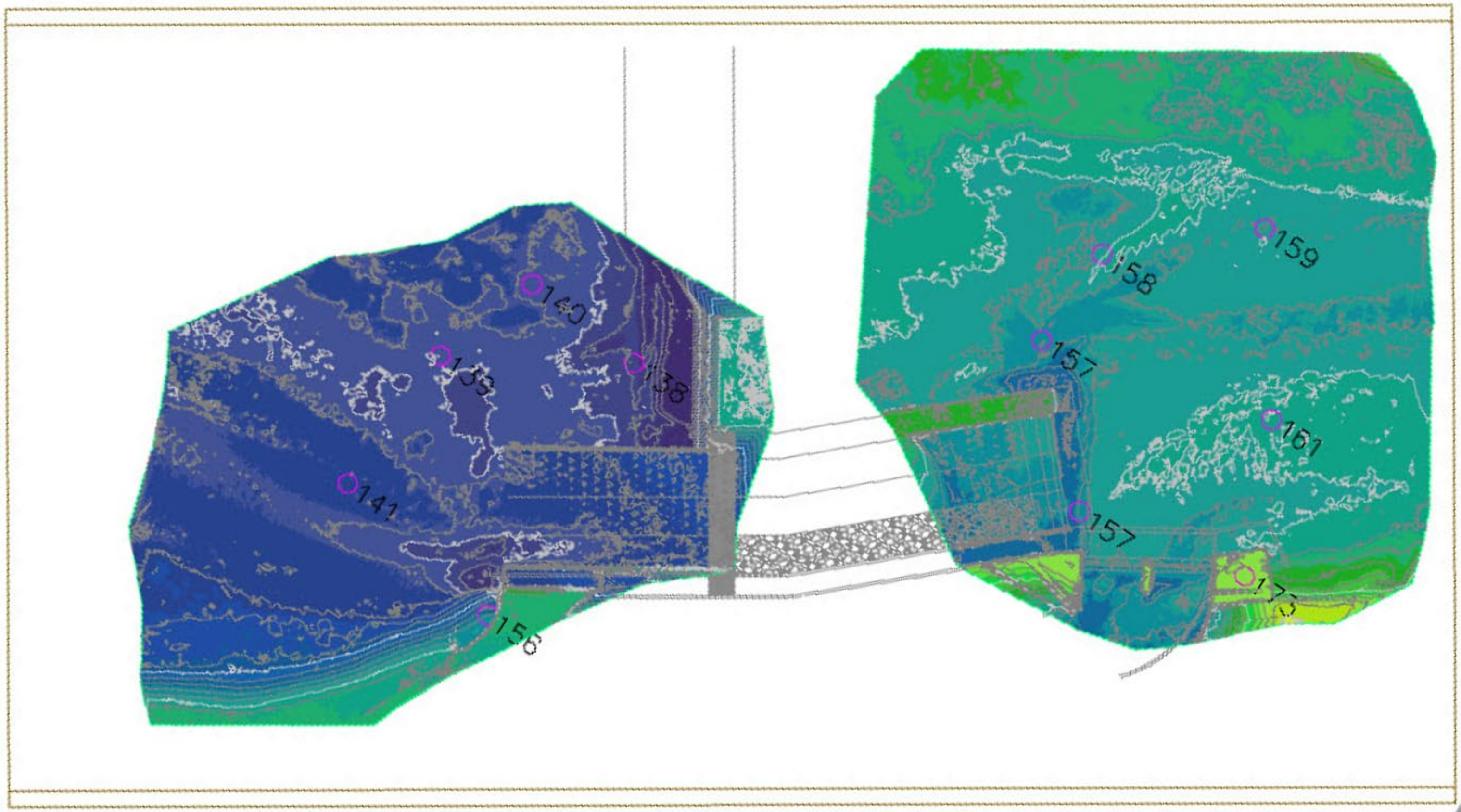

Figure B-26. Elevation contours after model run for MOD-6 design with flushing channel open at 3,000 ft^3/s river flow. Flow is from right to left.

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

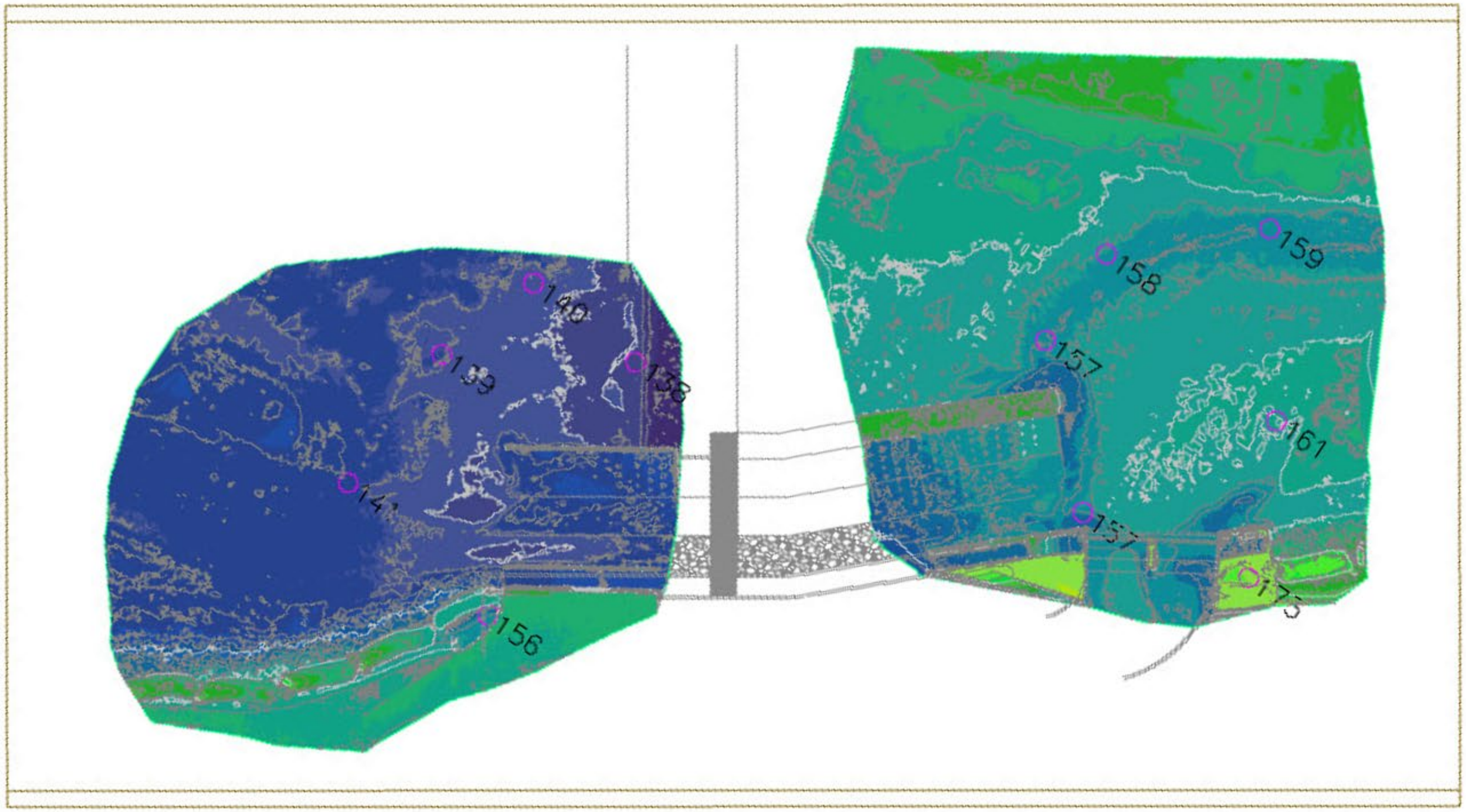

Figure B-27. Elevation contours after model run for MOD-6 design with flushing channel removed at 3,000 ft^3/s river flow. Flow is from right to left.

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

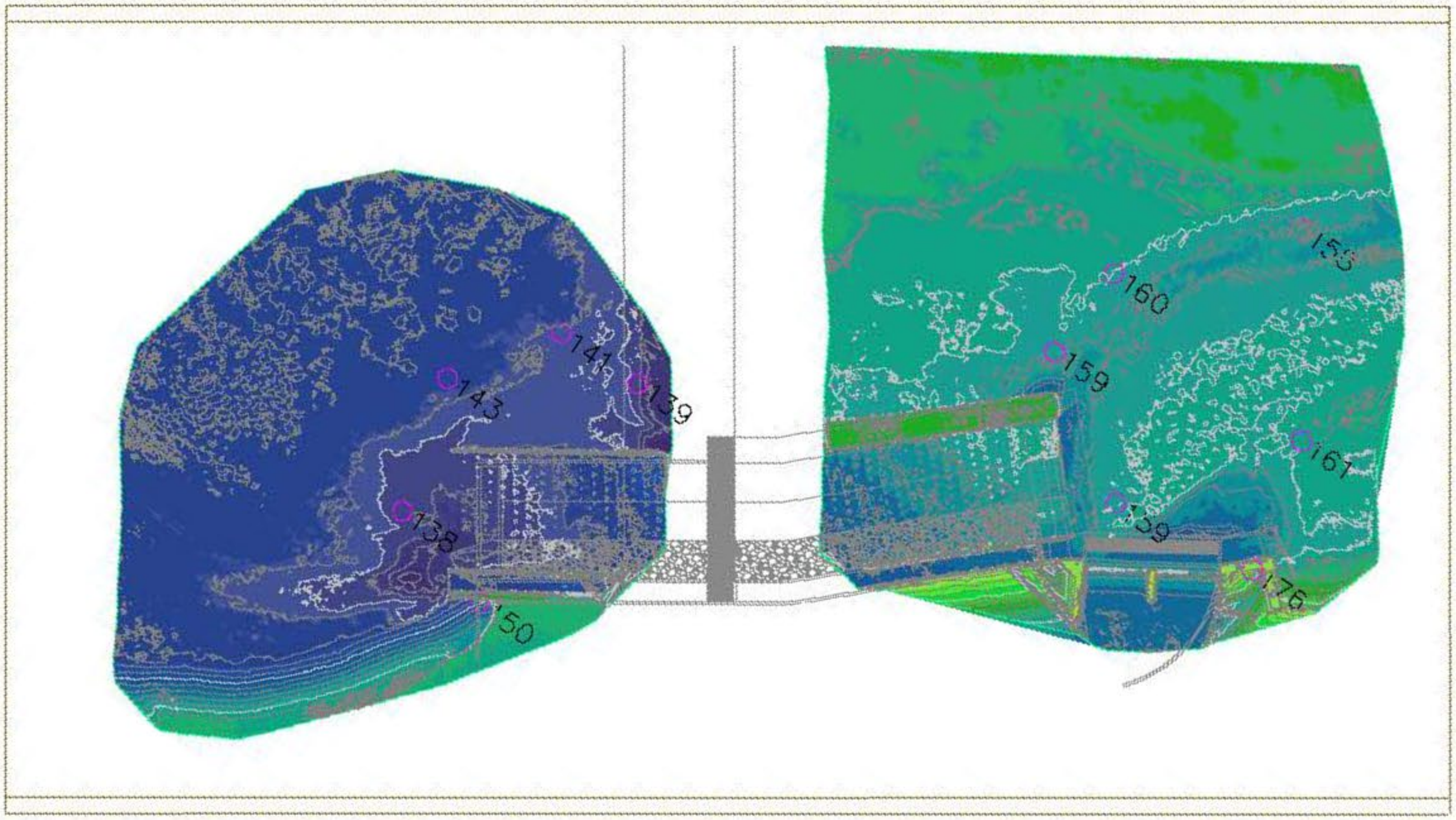

Figure B-28. Elevation contours after model run for MOD-9 design with flushing channel closed at 3,000 ft^3/s river flow. Flow is from right to left.

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

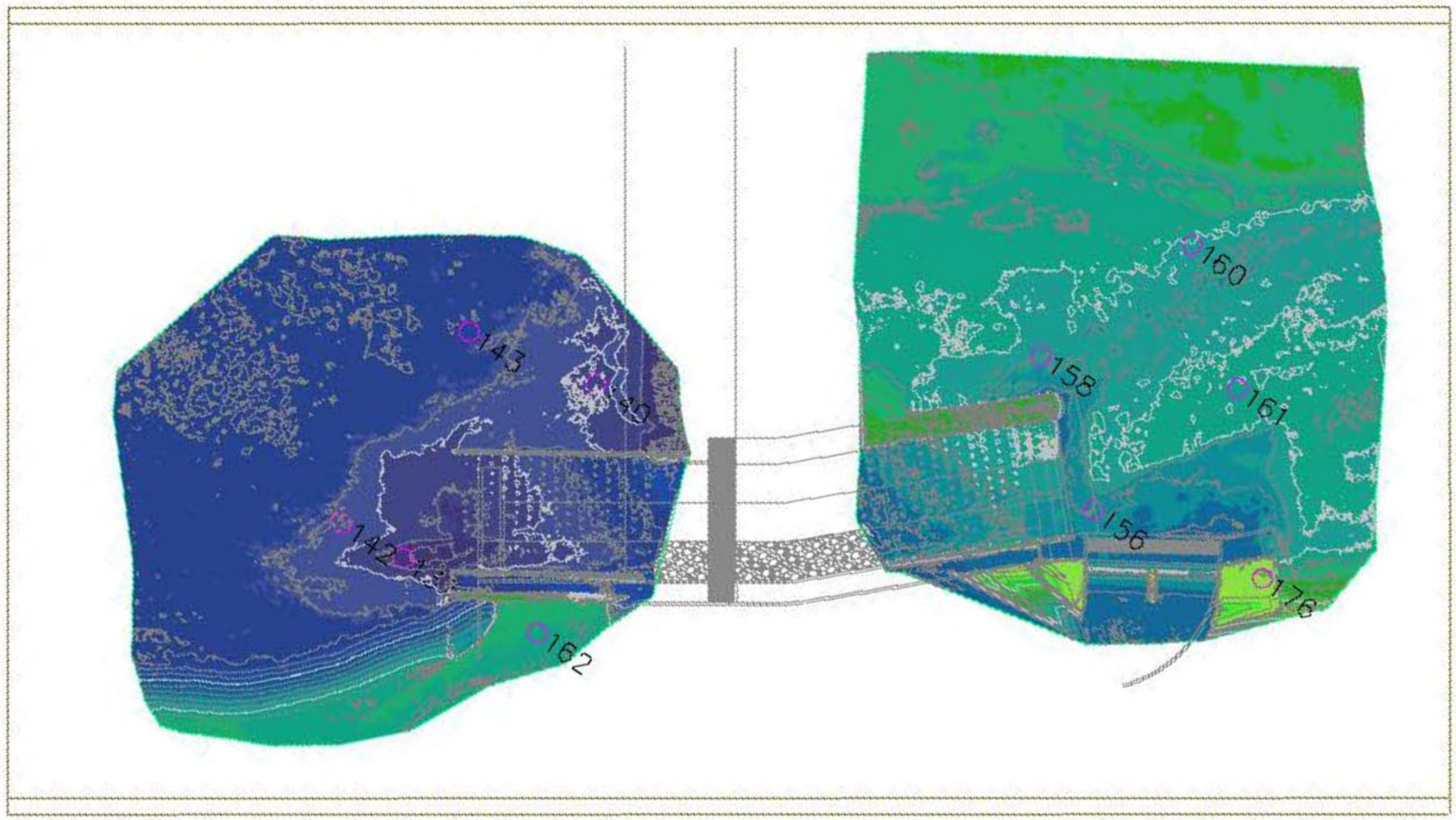

Figure B-29. Elevation contours after model run for MOD-9 design with flushing channel open at 3,000 ft^3/s river flow. Flow is from right to left.

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

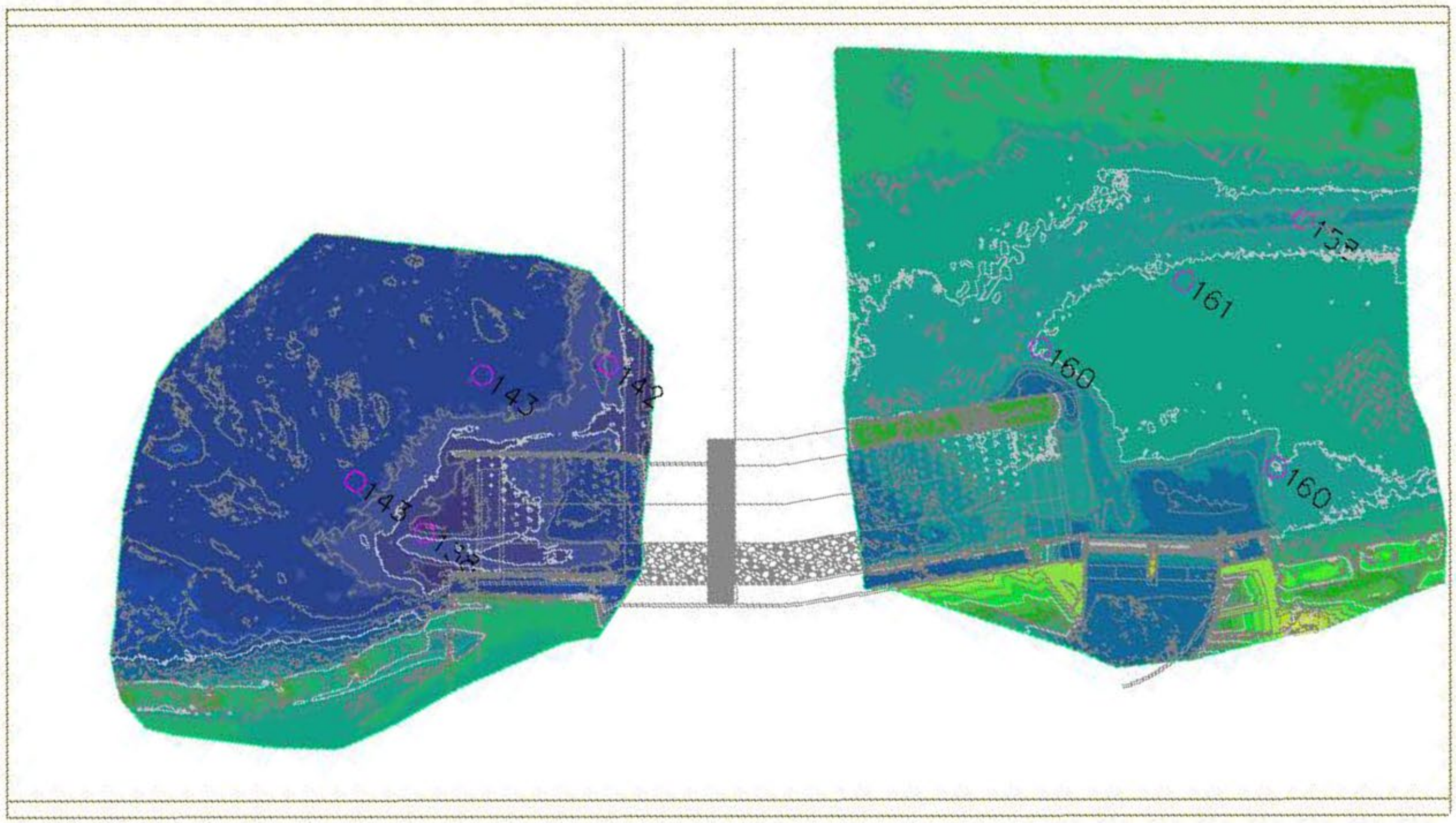

Figure B-30. Elevation contours after model run for MOD-9 design with flushing channel removed at 3,000 ft^3/s river flow. Flow is from right to left.

River Flow 6,000 ft³/s

MOD-6 Flushing Channel Closed

At 6,000 ft^3/s, flow widened the upstream channel and pushed the wetted edge further out on both sides, fully inundating the left depositional area. Fine and coarse sediment moved from the upstream channel and deposited on the upstream end of the hardened ramp and on the diversion sill against the canal intake gates. Sediment accumulated up to the top of the intake gates, reducing the ability of the gate to control the flow. The flow measured into the diversion was approximately 750 ft^3/s during the beginning of the test run as targeted. However, as sediment deposited against the intake gates the flow increased to about 1,000 ft^3/s due to sheet flow over the top of the gates into the diversion.

Downstream of the low flow section of the hardened ramp, scour occurred in a triangular pattern. Scour was concentrated immediately downstream of the ramp and widened to reach the left bank hardened topography. On the hardened ramp baffled section, the two downstream rows of baffles were inundated with sediment.

MOD-6 Flushing Channel Open

After the flushing channel was opened, only the sediment in front of intake gate 4 cleared. The left portion of the intake (gates 1-2) maintained sediment on the sill up to the top of the gates. Similar to the previous test with the flushing channel closed, sediment accumulated up to the top of the intake gates, reducing the ability of the gate to control the flow. The flow measured into the diversion was approximately 750 ft^3/s during the beginning of the test run as targeted. However, as sediment deposited against the intake gates the flow increased to about 1,000 ft^3/s due to sheet flow over the top of the gates into the diversion.

Downstream of the hardened ramp, sediment deposition occurred downstream of the baffled area. This depositional area ended downstream of the flushing channel. Some scour was observed from the end of the flushing channel to the downstream extent of the model.

MOD-6 Flushing Channel Removed

At 6,000 ft^3/s, flow widened the wetted edge of the main low-flow river channel, however a large part of elevation 164 ft on the left and right banks remained dry. Sediment transported from the channel and curved left towards the diversion intake and in front of the low flow channel. Similar to the previous test with the flushing channel closed, sediment accumulated up to the top of the intake gates, reducing the ability of the gate to control the flow. The flow measured into the diversion was approximately 750 ft^3/s during the beginning of the test run as targeted. However, as sediment deposited against the intake gates the flow increased to about 1,000 ft^3/s due to sheet flow over the top of the gates into the diversion.

The lower quarter of the hardened ramp baffled section was filled in with sediment across the entire width of the baffled section of the ramp. The low flow channel remained relatively clear of sediment. A scour pattern formed at the downstream end of the low flow channel to the edge of the left bank topography.

MOD-9 Flushing Channel Closed

At 6,000 ft^3/s, the left depositional area was inundated with flow, and much of the right depositional area was inundated at elevation 164 ft. Sediment from the main river channel continued to deposit on the intake apron and upstream end of the hardened ramp, which allowed water to flow from the edge of the upstream left depositional area directly to the low flow channel. The large recirculation zone seen at 3,000 ft^3/s was not present. However, the apron and sill of the intake did not accumulate any additional sediment.

Sediment deposition on the downstream baffled portion of the hardened ramp occurred mainly on the right side of the ramp with baffles covered by sediment over the downstream third of the ramp. Scour was concentrated immediately downstream of the hardened ramp in line with the low flow channel and widened to reach the left bank hardened topography.

MOD-9 Flushing Channel Open

After the flushing channel was opened, the apron in front of intake gates 3-4 was cleared of sediment. Additionally, the sand bar in front of the hardened ramp shifted to the left upstream of the flushing channel, with flow entering the hardened ramp and the flushing channel. The area of limited sediment deposition in front of the intake started to partially fill in, but the apron remained clear.

Downstream of the flushing channel, a recirculating eddy formed, creating a scour hole immediately downstream of the ramp. This scour pattern widened and continued downstream along the left bank. A scour pattern formed by the low flow channel on the previous run also continued downstream and curved slightly to the right.

MOD-9 Flushing Channel Removed

The upstream main river channel widened, eroding much of the left and right depositional areas from the intake to the dam crest. Flow moved directly towards the hardened ramp on the left and activated the entire dam crest on the right. Sediment accumulated upstream of the intake; however, it did not reach the top of the intake gates. The apron in front of intake gates 1-2 remained clear.

Downstream of the dam stilling basin, sediment accumulated in a curved semi-circular pattern skewed to the left. On the hardened ramp, sediment deposited in a transverse pattern over the baffled section for approximately the downstream third of the ramp. Some sediment also accumulated on the very downstream end of the low flow channel. Scour was observed downstream of the low flow channel; however, a distinct scour hole did not form.

Figure B-31. View looking downstream after dewatering for MOD-6 design with flushing channel closed at 6,000 ft^3/s.

Figure B-32. View looking upstream for MOD-6 design with flushing channel closed after 6,000 ft^3/s flow rate.

Figure B-33. View looking downstream after dewatering for MOD-9 design with flushing channel closed at 6,000 ft^3/s.

Figure B-34. View looking upstream for MOD-9 design with flushing channel closed after 6,000 ft^3/s flow rate.

Figure B-35. View looking downstream after dewatering for MOD-6 design with flushing channel open at 6,000 ft^3/s.

Figure B-36. View looking upstream for MOD-6 design with flushing channel open after 6,000 ft^3/s flow rate.

Figure B-37. View looking downstream after dewatering for MOD-9 design with flushing channel open at 6,000 ft^3/s.

Figure B-38. View looking upstream for MOD-9 design with flushing channel open after 6,000 ft^3/s flow rate.

Figure B-39. View looking downstream after dewatering for MOD-6 design with flushing channel removed at 6,000 ft^3/s.

Figure B-40. View looking upstream for MOD-6 design with flushing channel removed after 6,000 ft^3/s flow rate.

Figure B-41. View looking downstream after dewatering for MOD-9 design with flushing channel removed at 6,000 ft^3/s.

Figure B-42. View looking upstream for MOD-9 design with flushing channel removed after 6,000 ft^3/s flow rate.

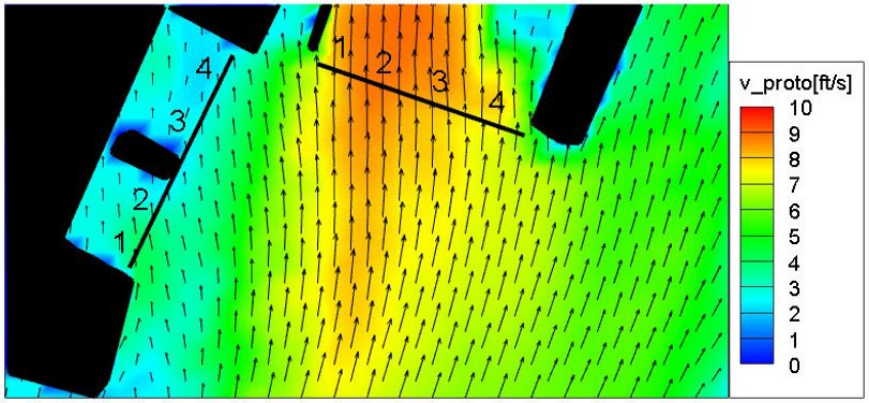

Figure B-43. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-6 design with flushing channel closed at 6,000 ft3/s river flow.

Figure B-44. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-6 design with flushing channel closed at 6,000 ft^3/s river flow.

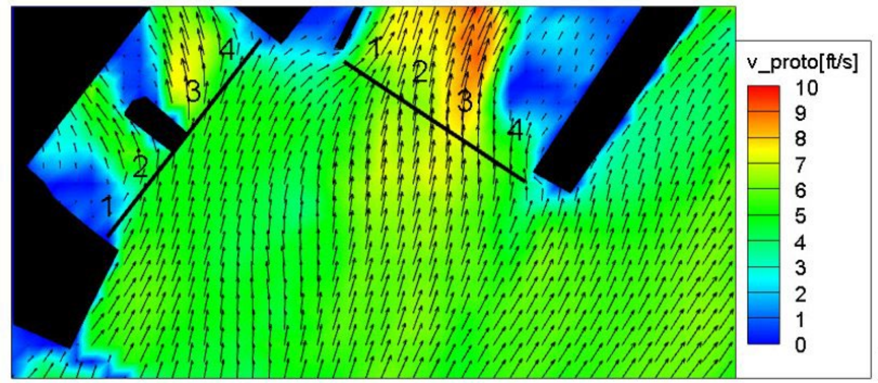

Figure B-45. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-9 design with flushing channel closed at 6,000 ft^3/s river flow.

Figure B-46. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-9 design with flushing channel closed at 6,000 ft^3/s river flow.

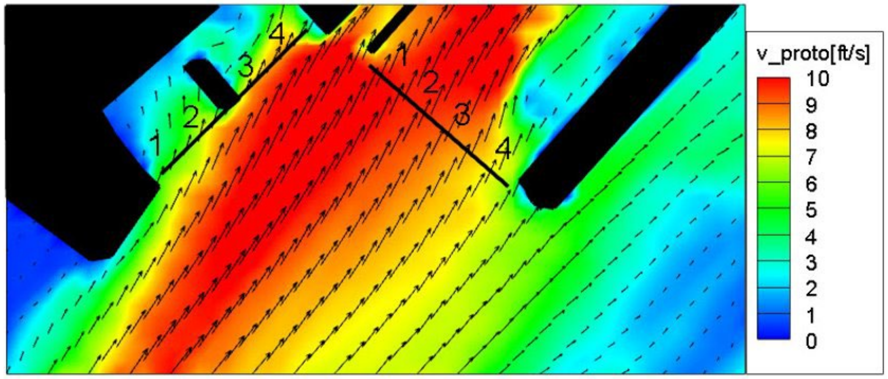

Figure B-47. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-6 design with flushing channel open at 6,000 ft^3/s river flow.

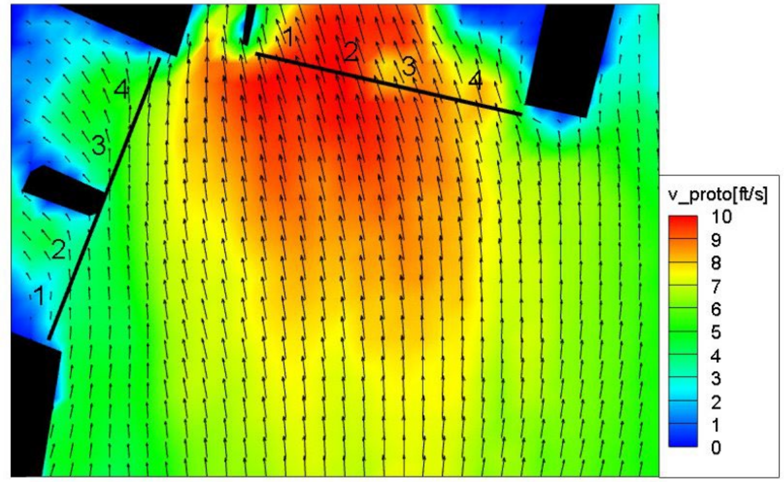

Figure B-49. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-9 design with flushing channel open at 6,000 ft^3/s river flow.

Figure B-48. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-6 design with flushing channel open at 6,000 ft^3/s river flow.

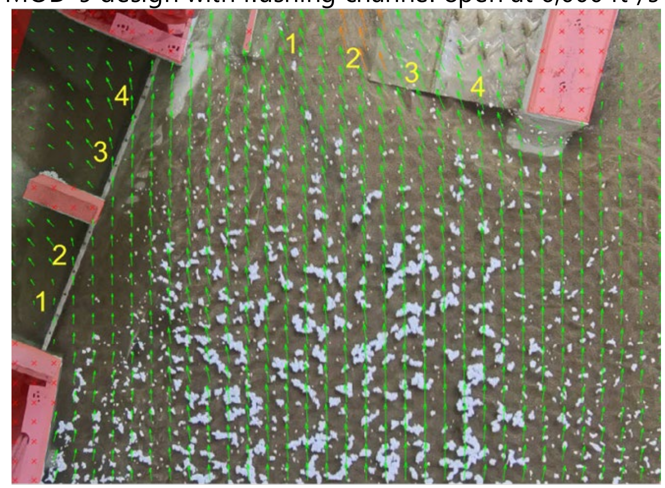

Figure B-50. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-9 design with flushing channel open at 6,000 ft^3/s river flow.

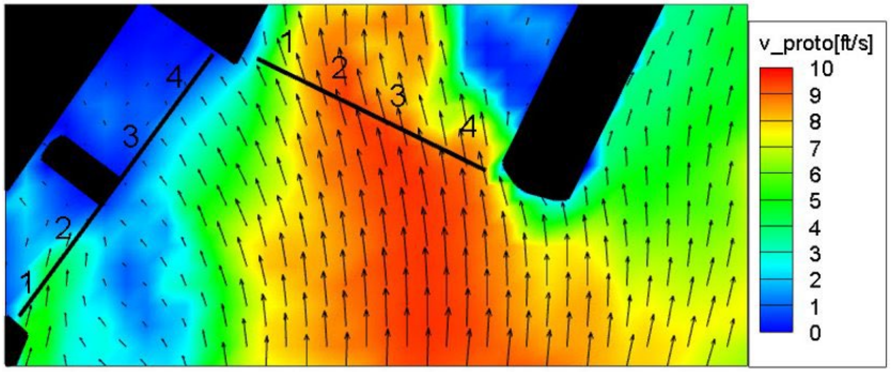

Figure B-51. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-6 design with flushing channel removed at 6,000 ft^3/s river flow.

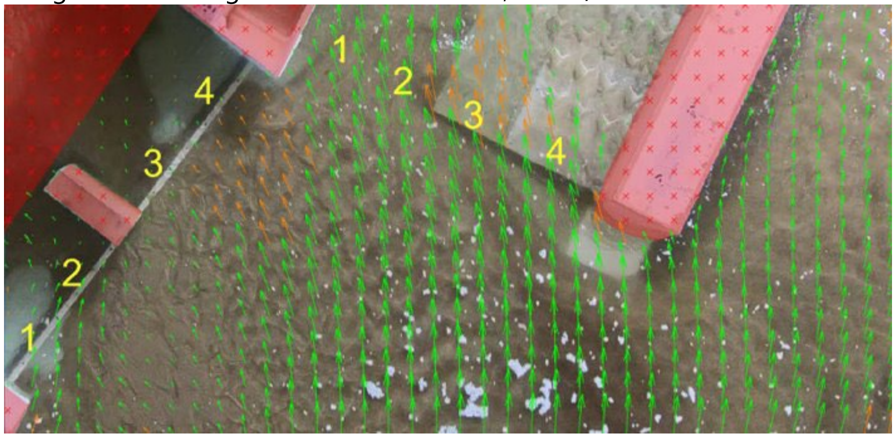

Figure B-52. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-6 design with flushing channel removed at 6,000 ft^3/s river flow.

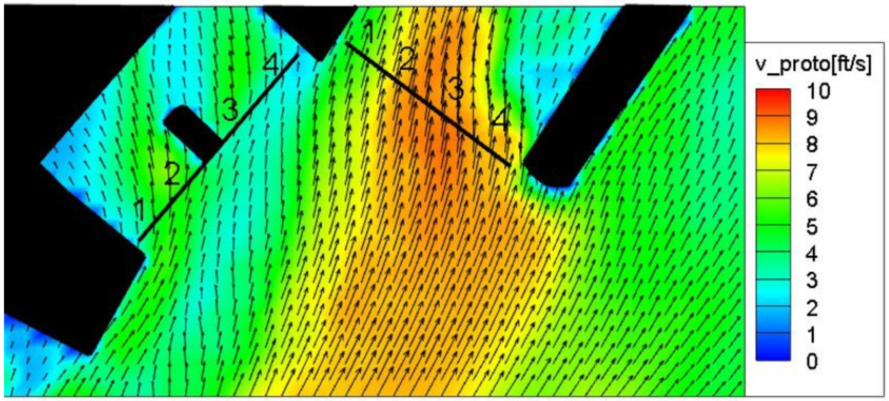

Figure B-53. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-9 design with flushing channel removed at 6,000 ft^3/s river flow.

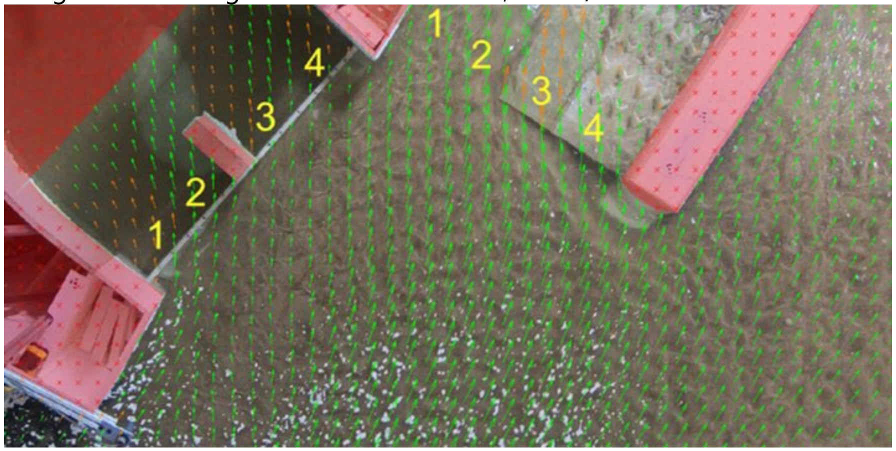

Figure B-54. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-9 design with flushing channel removed at 6,000 ft^3/s river flow.

Table B-7. Average prototype surface velocity magnitudes from LSPIV data at the diversion intake gates at 6,000 ft^3/s. Point "A" and "B" signify the left and right half of the gate, respectively.

	MOD-6 Average Prototype Surface Velocity Magnitude at Diversion Intake Gates (ft/s)			MOD-9 Average Prototype Surface Velocity Magnitude at Diversion Intake Gates (ft/s)		
Location	**Flushing Channel Closed**	**Flushing Channel Open**	**Flushing Channel Removed**	**Flushing Channel Closed**	**Flushing Channel Open**	**Flushing Channel Removed**
Gate 1A	3.3	5.3	2.9	0.1	1.7	3.0
Gate 1B	4.0	5.8	4.3	3.2	3.4	4.8
Gate 2A	3.4	6.8	3.4	4.4	3.8	5.2
Gate 2B	2.4	6.7	1.2	4.7	3.6	4.5
Gate 3A	2.7	8.2	0.8	5.5	5.1	3.8
Gate 3B	2.6	8.4	1.4	4.7	5.9	3.2
Gate 4A	2.6	8.4	1.0	3.7	5.9	2.8
Gate 4B	2.5	4.5	0.3	1.4	2.7	2.1

Table B-8. Average prototype surface velocity magnitudes from LSPIV data at hardened ramp exit at 6,000 ft^3/s. Point "A" and "B" signify the left and right half of the gate, respectively.

	MOD-6 Average Prototype Surface Velocity Magnitude at Hardened Ramp Exit (ft/s)			MOD-9 Average Prototype Surface Velocity Magnitude at Hardened Ramp Exit (ft/s)		
Location	**Flushing Channel Closed**	**Flushing Channel Open**	**Flushing Channel Removed**	**Flushing Channel Closed**	**Flushing Channel Open**	**Flushing Channel Removed**
Gate 1A	6.5	9.4	3.0	4.0	7.5	4.5
Gate 1B	8.4	10.0	7.1	5.5	9.8	6.1
Gate 2A	8.8	9.7	8.9	6.3	10.0	7.8
Gate 2B	8.5	9.5	9.3	6.4	9.1	8.7
Gate 3A	8.2	8.9	9.2	7.5	8.5	8.7
Gate 3B	7.8	8.4	8.7	6.8	8.4	8.7
Gate 4A	7.6	7.5	8.8	5.7	8.1	8.1
Gate 4B	6.1	6.2	8.3	4.1	4.7	7.5

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

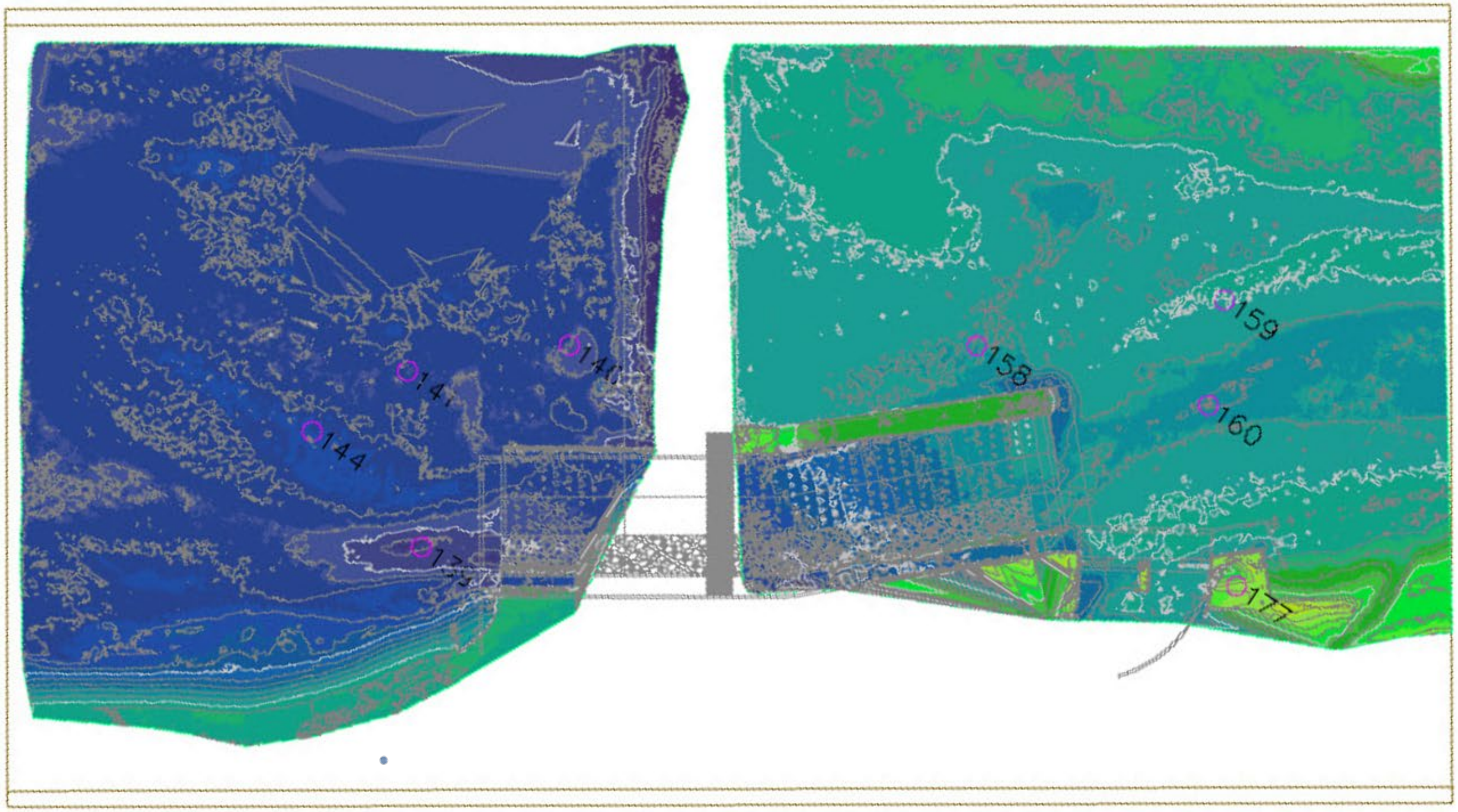

Figure B-55. Elevation contours after model run for MOD-6 design with flushing channel closed at 6,000 ft^3/s river flow. Flow is from right to left.

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

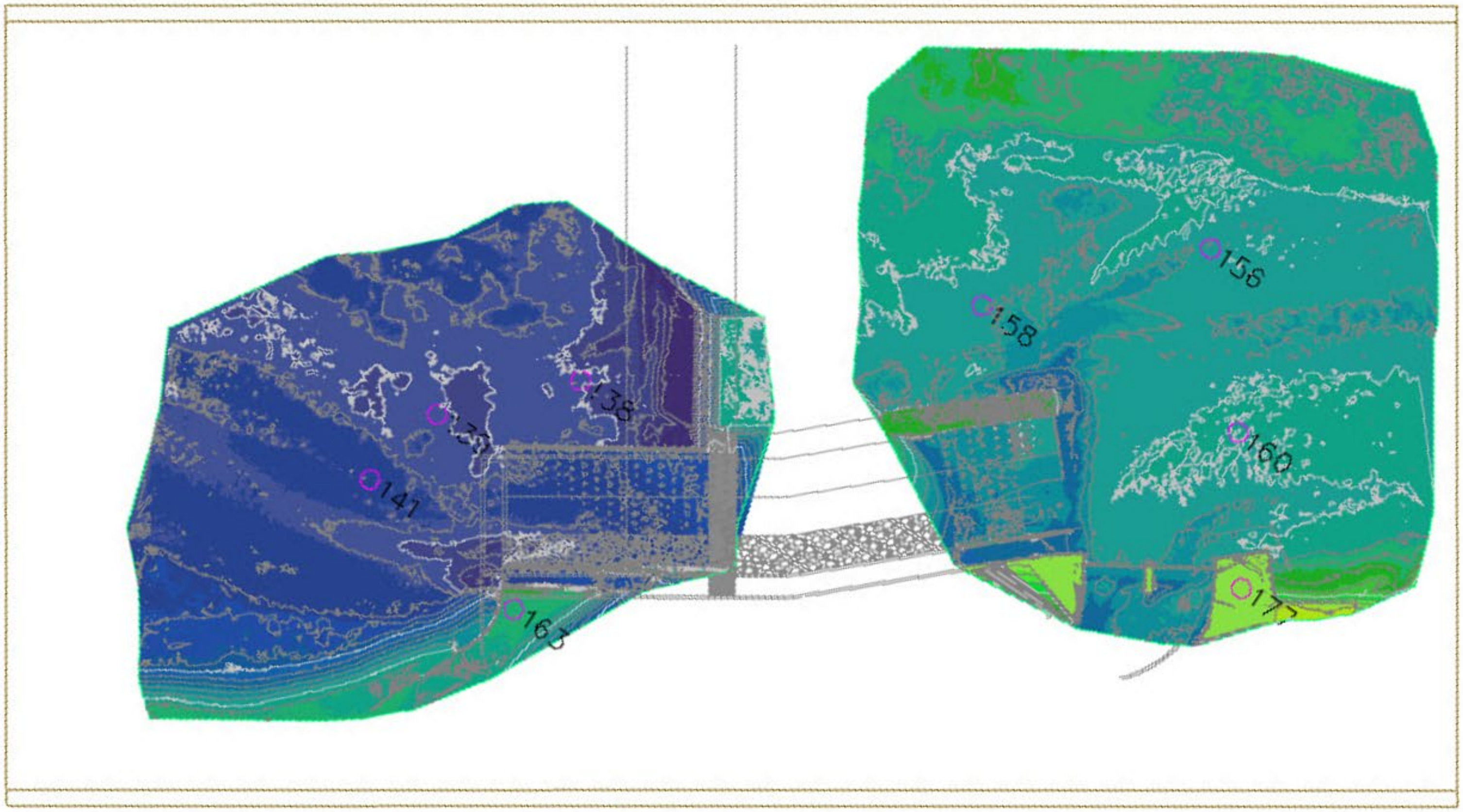

Figure B-56. Elevation contours after model run for MOD-6 design with flushing channel open at 6,000 ft^3/s river flow. Flow is from right to left.

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

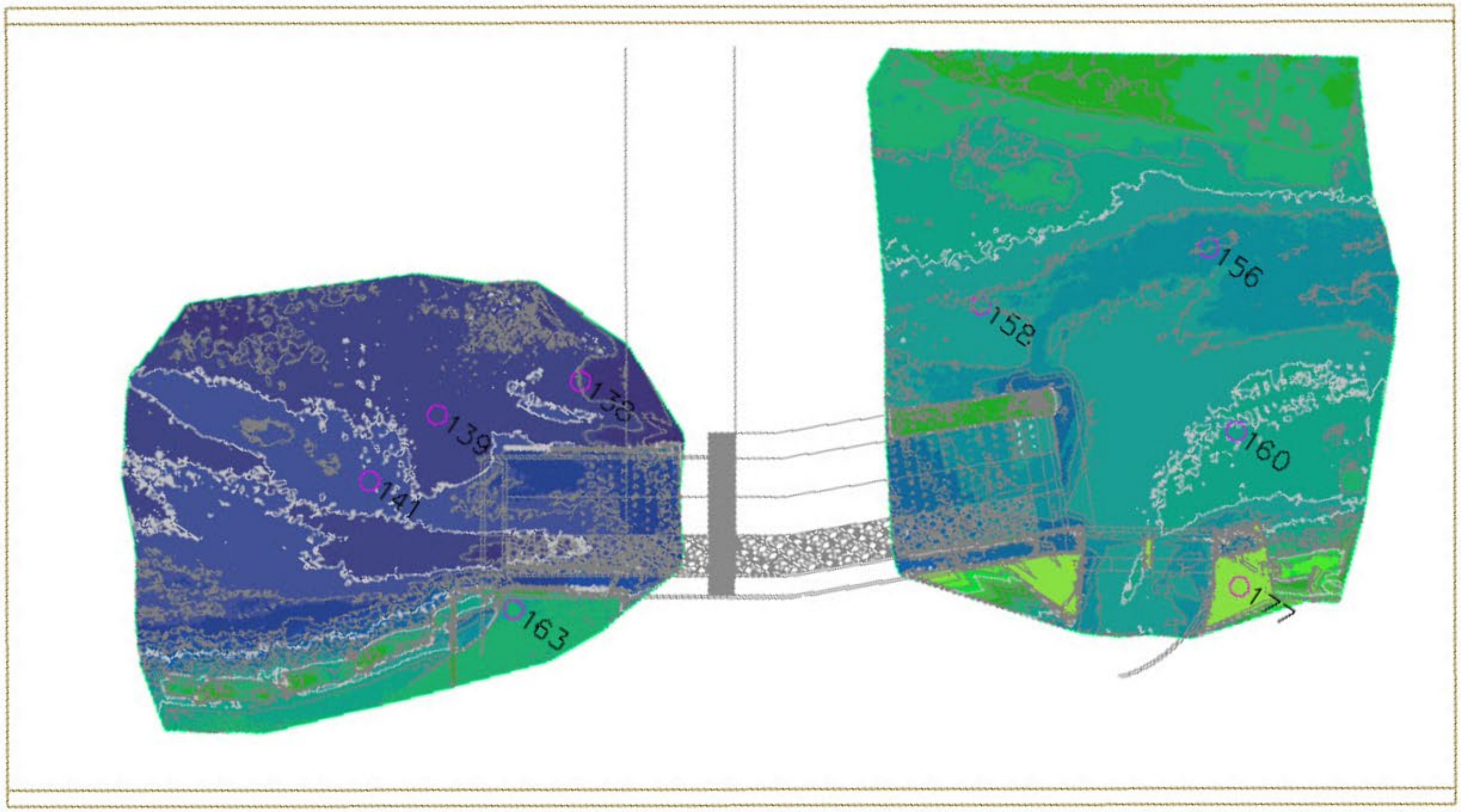

Figure B-57. Elevation contours after model run for MOD-6 design with flushing channel removed at 6,000 ft^3/s river flow. Flow is from right to left.

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

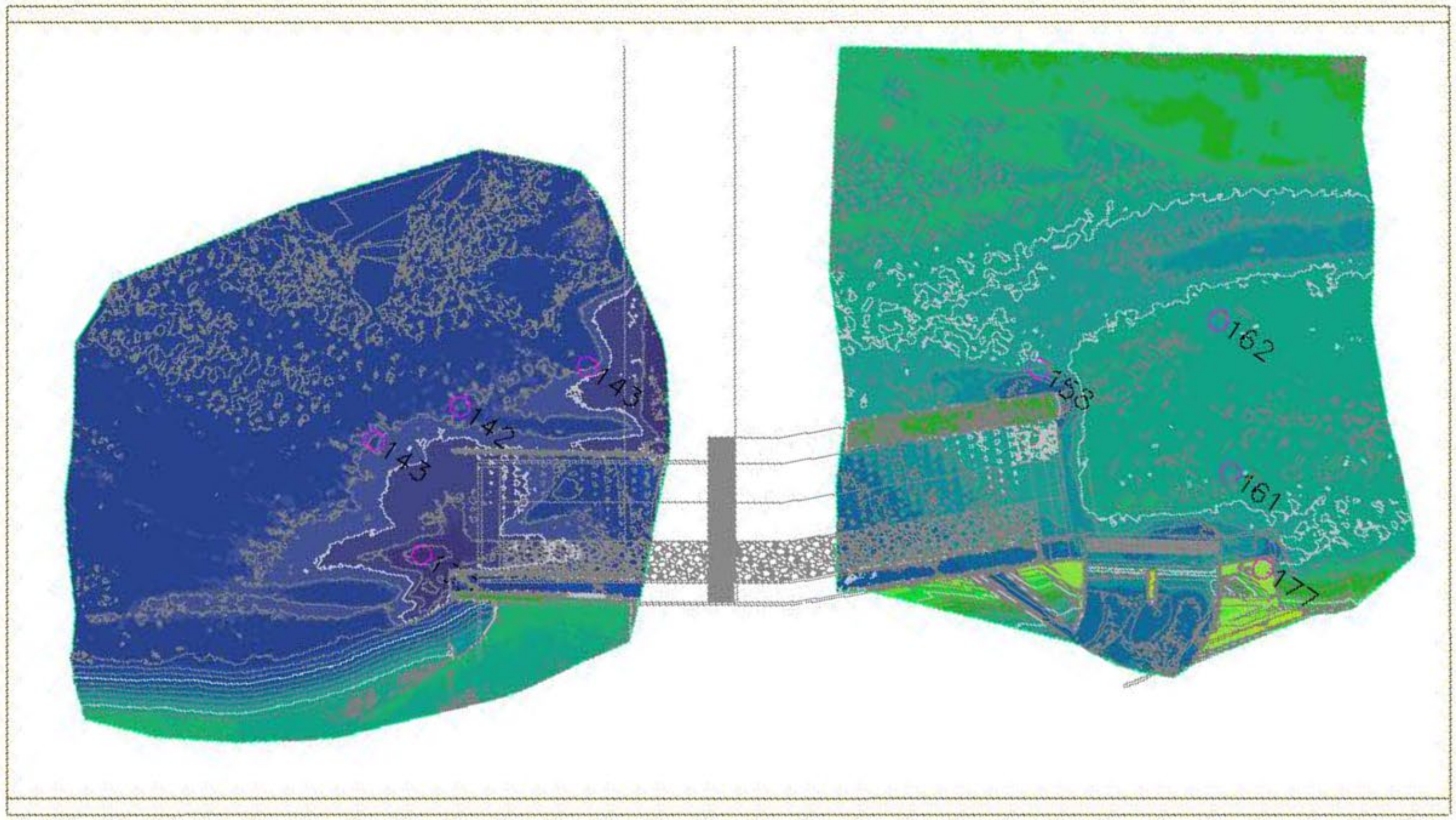

Figure B-58. Elevation contours after model run for MOD-9 design with flushing channel closed at 6,000 ft^3/s river flow. Flow is from right to left.

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

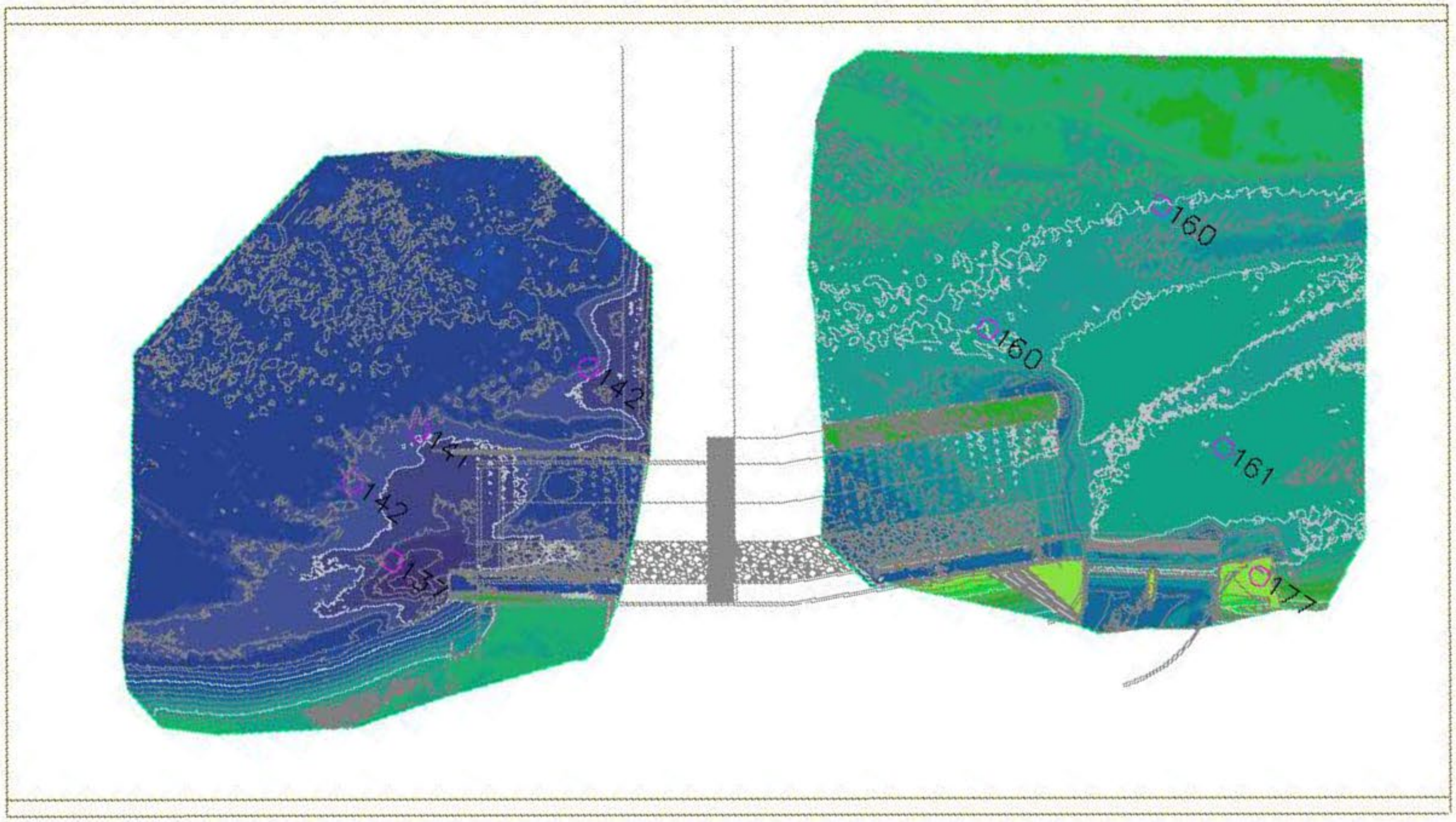

Figure B-59. Elevation contours after model run for MOD-9 design with flushing channel open at 6,000 ft^3/s river flow. Flow is from right to left.

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
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23	175.00	177.50	
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25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

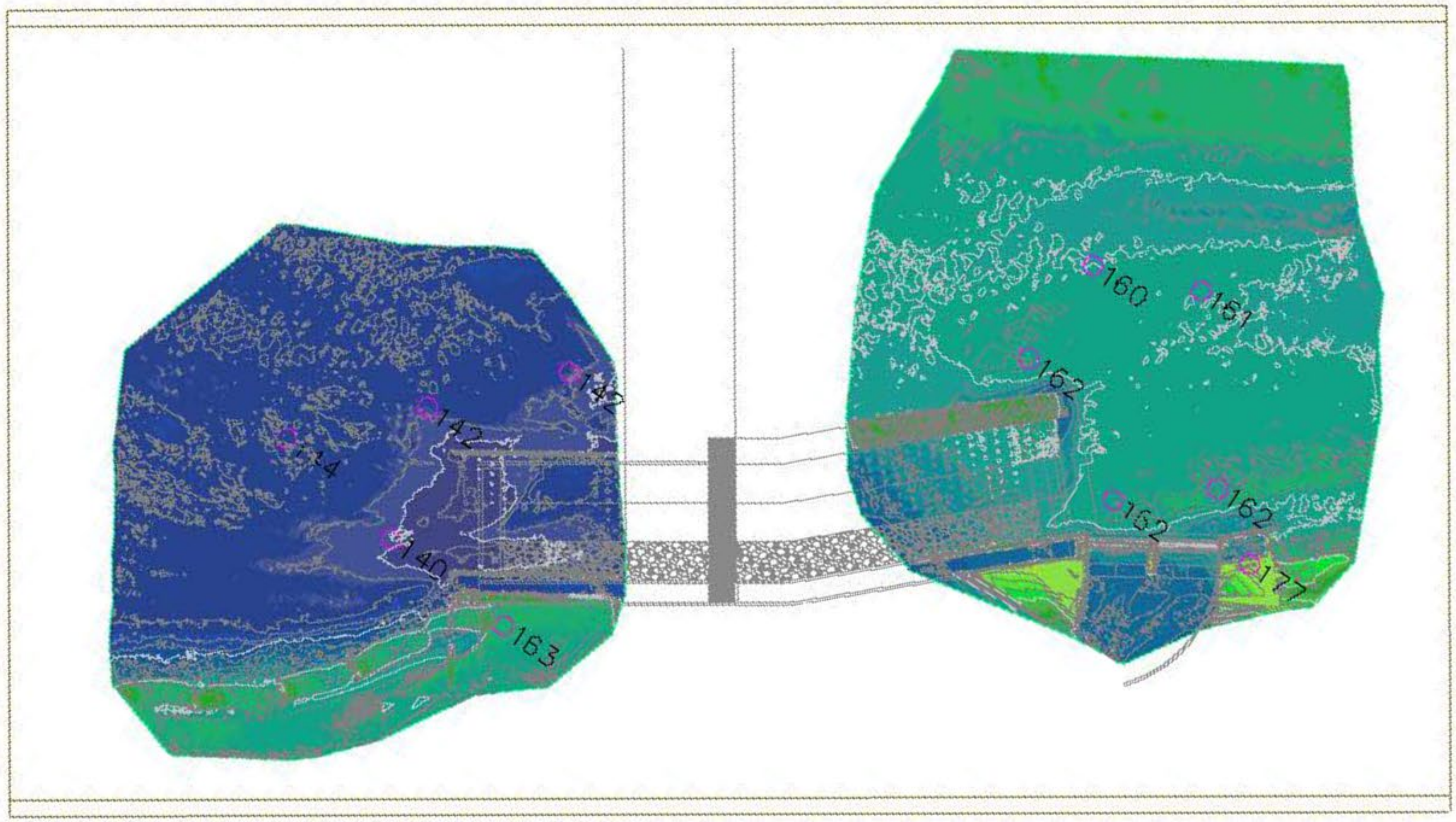


Figure B-60. Elevation contours after model run for MOD-9 design with flushing channel removed at 6,000 ft^3/s river flow. Flow is from right to left.

River Flow 12,000 ft^3/s

MOD-6 Flushing Channel Closed
At 12,000 ft^3/s the main river channel shifted to the left, more in line with the bullnose of the hardened ramp wall. The portion of the left depositional area that remained became uniform in elevation, level with the entrance to the hardened ramp. This caused sediment to accumulate uniformly in front of the hardened ramp and intake, with some of the apron exposed in front of the closed flushing channel.

Some sediment accumulated on the downstream baffled portion of the hardened ramp. This sediment was not deep enough to cover the baffles and the baffles still influenced flow coming down the ramp. No sediment accumulated in the low flow channel, with some scour downstream of the channel. Sediment deposited downstream of the dam stilling basin which extended downstream from the exit of the hardened ramp. A reverse roller formed outside the right wall of the hardened ramp. This pulled material away from the wall and may be a concern for undermining the wall.

MOD-6 Flushing Channel Open
Immediately after the flushing channel was opened, the area around intake gate 4 was cleared of sediment. However, sediment levels were maintained in front of intake gates 1-2 and the hardened ramp. At this flow rate, larger sized rocks as well as significant amounts of fine and coarse sands moved down the flushing channel from the main river channel. The bullnose created eddies around the right side towards the dam crest and sediment deposition occurred against the right side of the ramp wall.

Downstream of the flushing channel, a scour hole formed which continued to the end of the model extents. A reverse roller formed downstream of the flushing channel exit which pulled material back toward the structure, allowing a scour hole to form approximately 15-20 ft downstream of the flushing channel exit.

MOD-6 Flushing Channel Removed
The main upstream river channel divided into two dominant channels: one towards the left that aligned with the bullnose and one following the right topography elevation 164 ft to the dam crest. The new sand bar that separated these two channels may have caused more flow to be diverted to the dam crest than when the flushing channel was included. All the intake gates were partially buried by sediment deposition and sediment deposited in front of the low flow channel.

A significant portion of the baffled and low flow channel on the hardened ramp were filled with sediment downstream in a diagonal sediment bar starting at the change in angle about midway down the hardened ramp. The lower third of baffles were completely covered with the sediment. Any existing scour holes downstream of the low flow channel from previous flows were filled in.

MOD-9 Flushing Channel Closed
At 12,000 ft^3/s, the main upstream river channel divided into two dominant channels: one towards the left that aligned with the bullnose and one following the right topography elevation 164 ft to the dam crest similar to the MOD-6 configuration with the flushing channel removed. The new sand bar that separated these two channels may have caused more flow to be diverted to the dam crest. Sediment filled in the apron in front of the intake; however, the sill in front of the gates remained clear. Sediment also deposited on the apron of the hardened ramp as a continuation of the left depositional area.

Approximately one third of the baffled and low flow channel on the hardened ramp were filled with sediment downstream forming a diagonal sediment bar from the shear zone along the ramp wall on the right. Only baffles along the sandbar were covered, while the surrounding baffles were still exposed. A scour hole developed downstream of the low flow channel and continued to the end of the model extents.

MOD-9 Flushing Channel Open

After the flushing channel was opened, the apron in front of intake gate 4 was cleared, as well as part of gate 3. The area in front of gates 1-2 remained covered in sediment. The flushing channel moved coarse and fine sediment along with occasional larger rocks. The area in front of the hardened ramp maintained its sediment deposition pattern.

Scour from the configuration with the flushing channel closed shifted to the flushing channel exit and continued to the end of the model extents. Sediment deposition remained unchanged in the hardened ramp with a large low velocity region on the right side.

MOD-9 Flushing Channel Removed

After the flushing channel was removed, flow patterns and sediment deposition patterns upstream of the dam were similar to the MOD-6 configuration with the flushing channel closed. The main upstream river channel divided into two dominant channels: one towards the left that aligned with the bullnose and one following the right topography elevation 164 ft to the dam crest. The new sand bar that separated these two channels may have caused more flow to be diverted to the dam crest. Sediment deposition reached the top of intake gates 1-2 and filled in the upstream end of the hardened ramp low flow channel. The sill in front of intake gate 4 remained clear of sediment due to the scour around the edge of the upstream wing wall.

Approximately one third of the baffles and low flow channel on the hardened ramp were filled with sediment downstream in a diagonal sandbar. Only baffles along the sandbar were covered with the surrounding baffles were still exposed. A scour hole developed downstream of the low flow channel and continued to the end of the model extents.

Figure B-61. View looking downstream after dewatering for MOD-6 design with flushing channel closed at 12,000 ft^3/s.

Figure B-62. View looking upstream for MOD-6 design with flushing channel closed after 12,000 ft^3/s flow rate.

Figure B-63. View looking downstream after dewatering for MOD-9 design with flushing channel closed at 12,000 ft^3/s.

Figure B-64. View looking upstream for MOD-9 design with flushing channel closed after 12,000 ft^3/s flow rate.

Figure B-65. View looking downstream after dewatering for MOD-6 design with flushing channel open at 12,000 ft^3/s.

Figure B-66. View looking upstream for MOD-6 design with flushing channel open after 12,000 ft^3/s flow rate.

Figure B-67. View looking downstream after dewatering for MOD-9 design with flushing channel open at 12,000 ft^3/s.

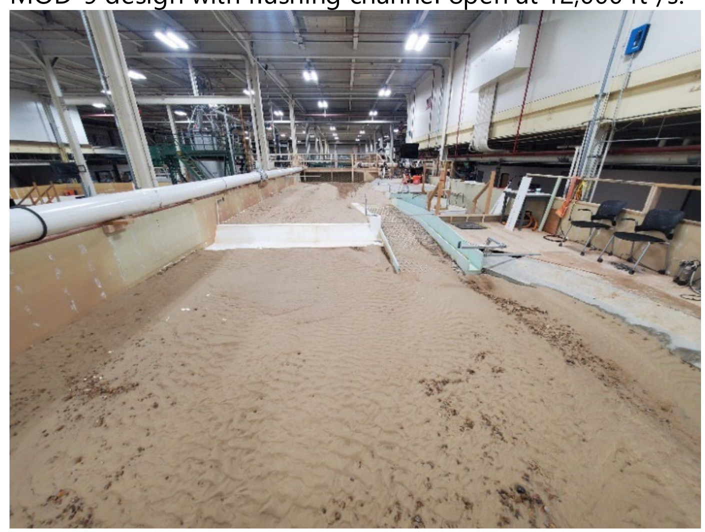


Figure B-68. View looking upstream for MOD-9 design with flushing channel open after 12,000 ft^3/s flow rate.

Figure B-69. View looking downstream after dewatering for MOD-6 design with flushing channel removed at 12,000 ft3/s.

Figure B-70. View looking upstream for MOD-6 design with flushing channel removed after 12,000 ft^3/s flow rate.

Figure B-71. View looking downstream after dewatering for MOD-9 design with flushing channel removed at 12,000 ft^3/s.

Figure B-72. View looking upstream for MOD-9 design with flushing channel removed after 12,000 ft^3/s flow rate.

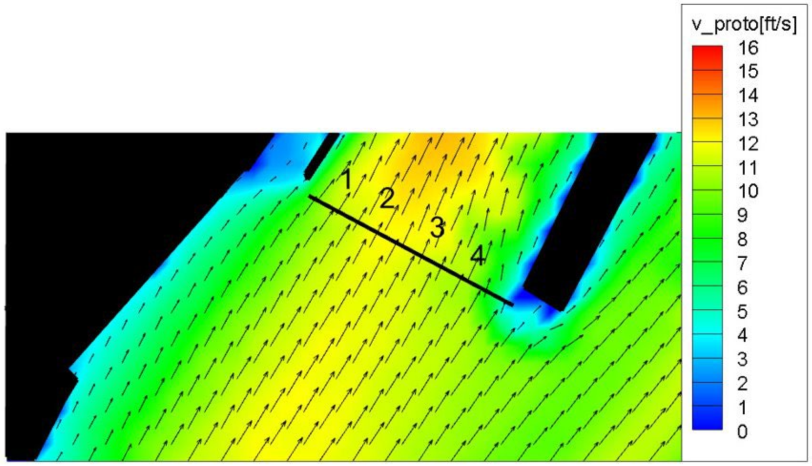


Figure B-73. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-6 design with flushing channel closed at 12,000 ft^3/s river flow.

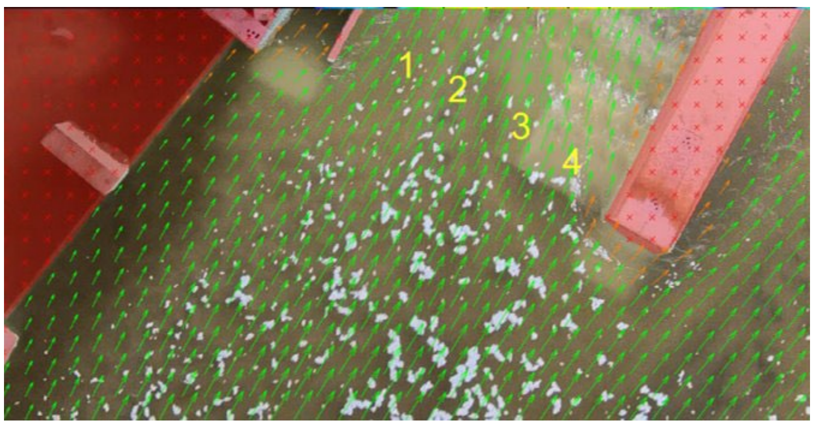


Figure B-74. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-6 design with flushing channel closed at 12,000 ft^3/s river flow.

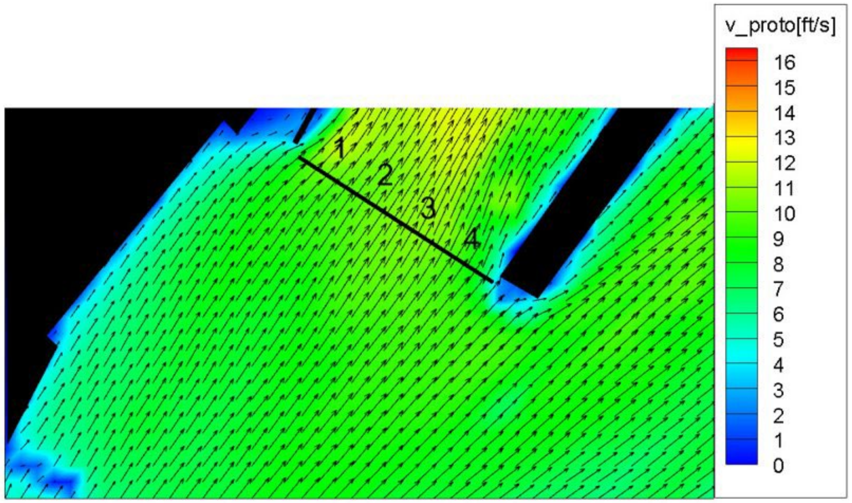


Figure B-75. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-9 design with flushing channel closed at 12,000 ft^3/s river flow.

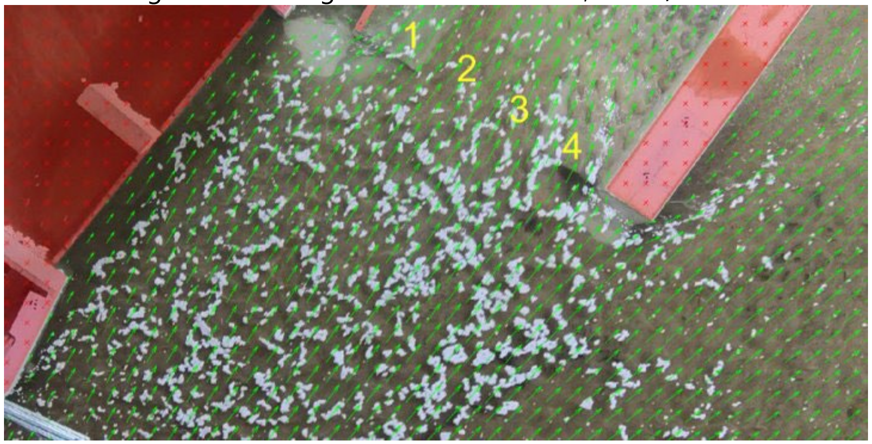


Figure B-76. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-9 design with flushing channel closed at 12,000 ft^3/s river flow.

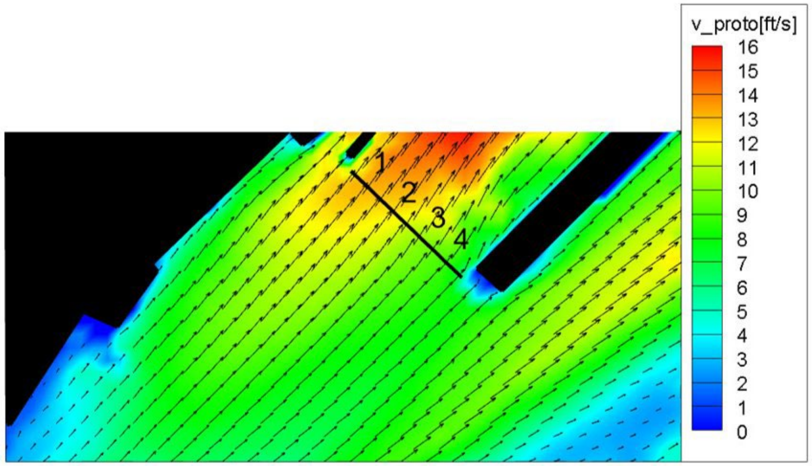


Figure B-77. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-6 design with flushing channel open at 12,000 ft^3/s river flow.

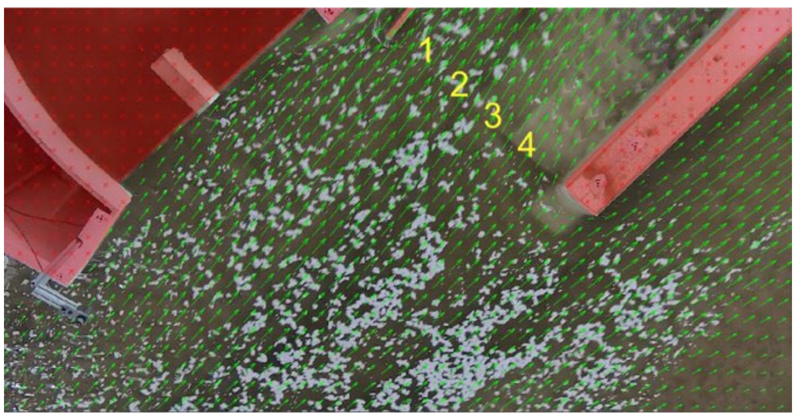


Figure B-78. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-6 design with flushing channel open at 12,000 ft^3/s river flow.

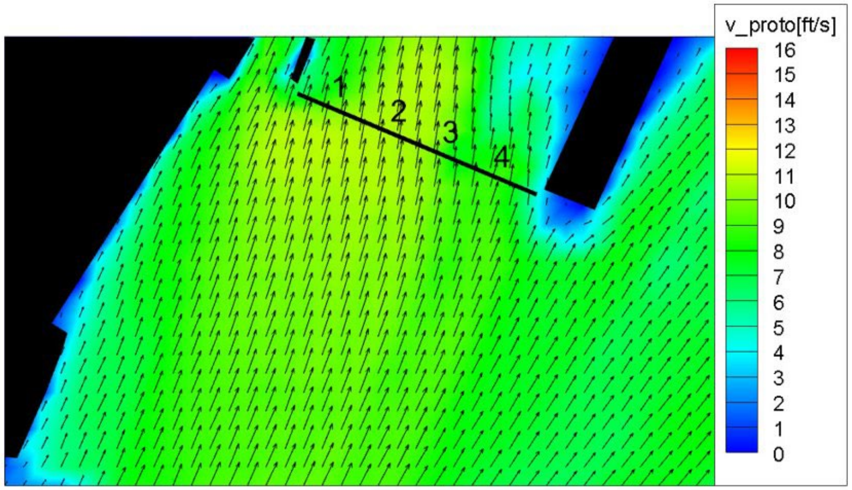


Figure B-79. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-9 design with flushing channel open at 12,000 ft^3/s river flow.

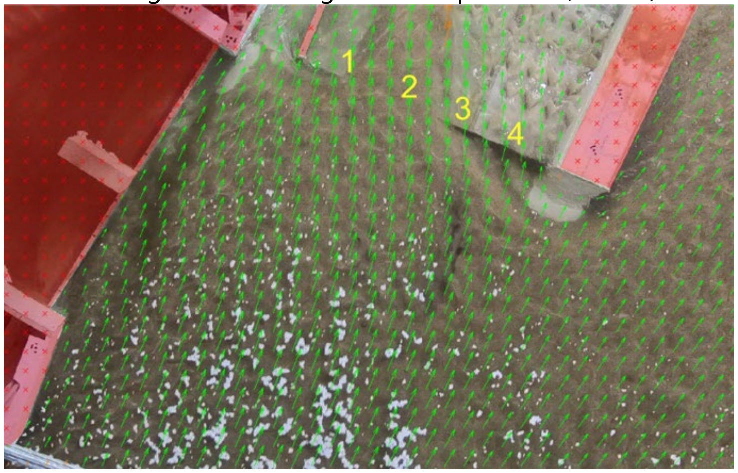


Figure B-80. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-9 design with flushing channel open at 12,000 ft^3/s river flow.

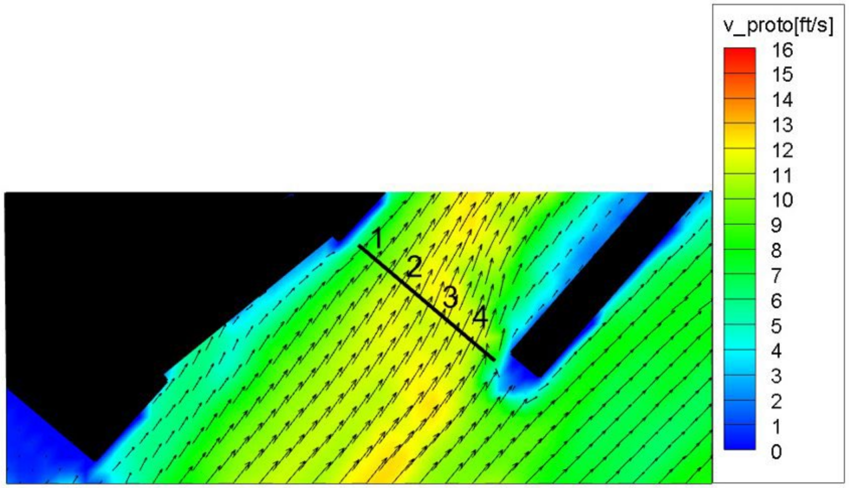


Figure B-81. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-6 design with flushing channel removed at 12,000 ft^3/s river flow.

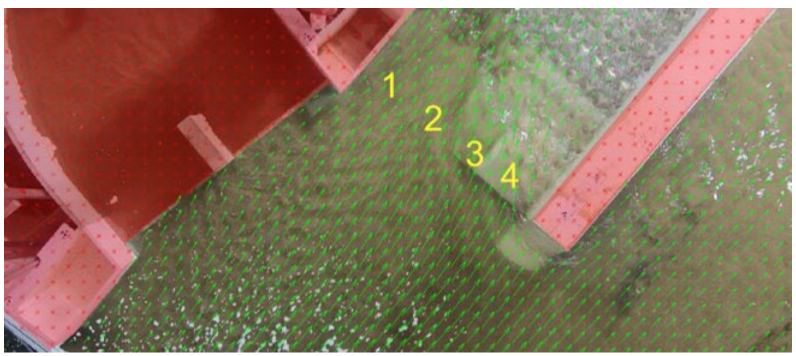


Figure B-82. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-6 design with flushing channel removed at 12,000 ft^3/s river flow.

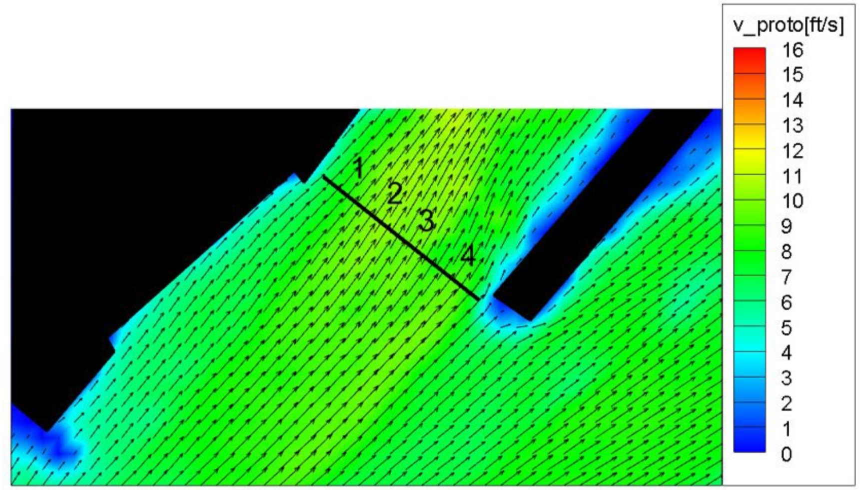


Figure B-83. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-9 design with flushing channel removed at 12,000 ft^3/s river flow.

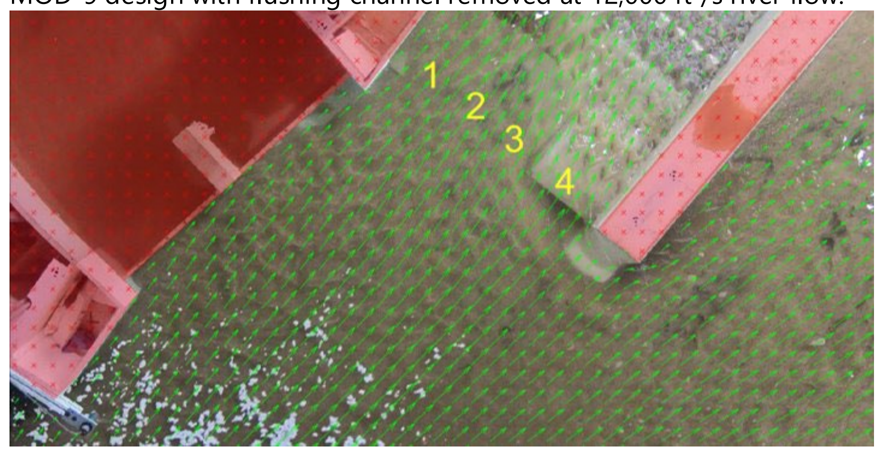


Figure B-84. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-9 design with flushing channel removed at 12,000 ft^3/s river flow.

Table B-9. Average prototype surface velocity magnitudes from LSPIV data at hardened ramp exit at 12,000 ft^3/s. Point "A" and "B" signify the left and right half of the gate, respectively.

	MOD-6 Average Prototype Surface Velocity Magnitude at Hardened Ramp Exit (ft/s)			MOD-9 Average Prototype Surface Velocity Magnitude at Hardened Ramp Exit (ft/s)		
Location	**Flushing Channel Closed**	**Flushing Channel Open**	**Flushing Channel Removed**	**Flushing Channel Closed**	**Flushing Channel Open**	**Flushing Channel Removed**
Gate 1A	8.5	11.6	6.1	8.0	7.1	6.1
Gate 1B	11.1	13.2	9.4	10.1	9.8	8.1
Gate 2A	11.7	12.8	10.9	9.9	10.7	9.8
Gate 2B	11.9	12.1	11.5	10.4	10.7	10.2
Gate 3A	11.5	10.8	11.6	10.7	10.0	9.5
Gate 3B	10.7	9.8	11.5	10.4	8.1	8.8
Gate 4A	8.5	8.9	11.0	8.9	8.6	9.4
Gate 4B	2.3	6.0	6.7	4.5	4.5	7.2

Elevations Table

Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

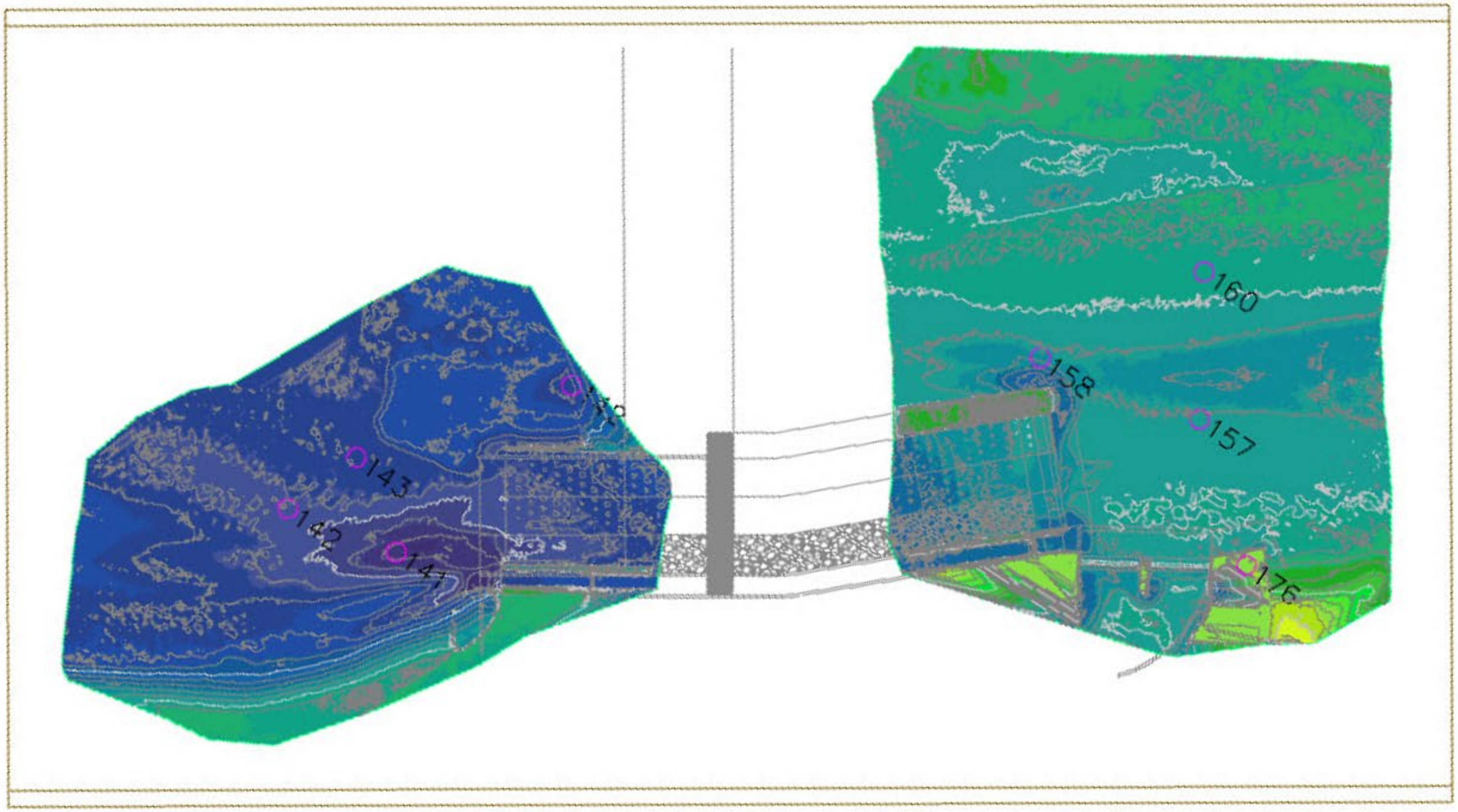


Figure B-85. Elevation contours after model run for MOD-6 design with flushing channel closed at 12,000 ft^3/s river flow. Flow is from right to left.

Elevations Table

Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

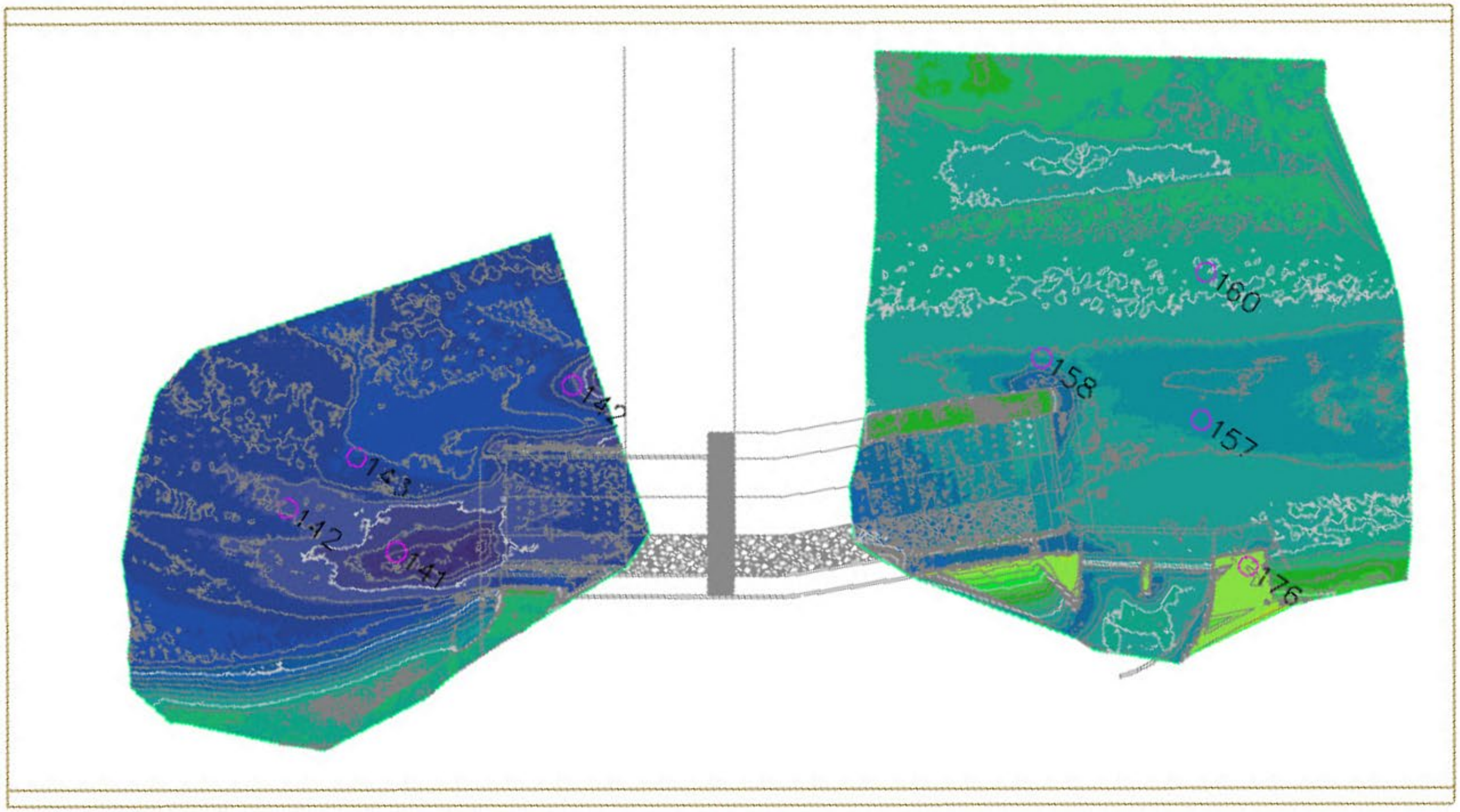


Figure B-86. Elevation contours after model run for MOD-6 design with flushing channel open at 12,000 ft^3/s river flow. Flow is from right to left.

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

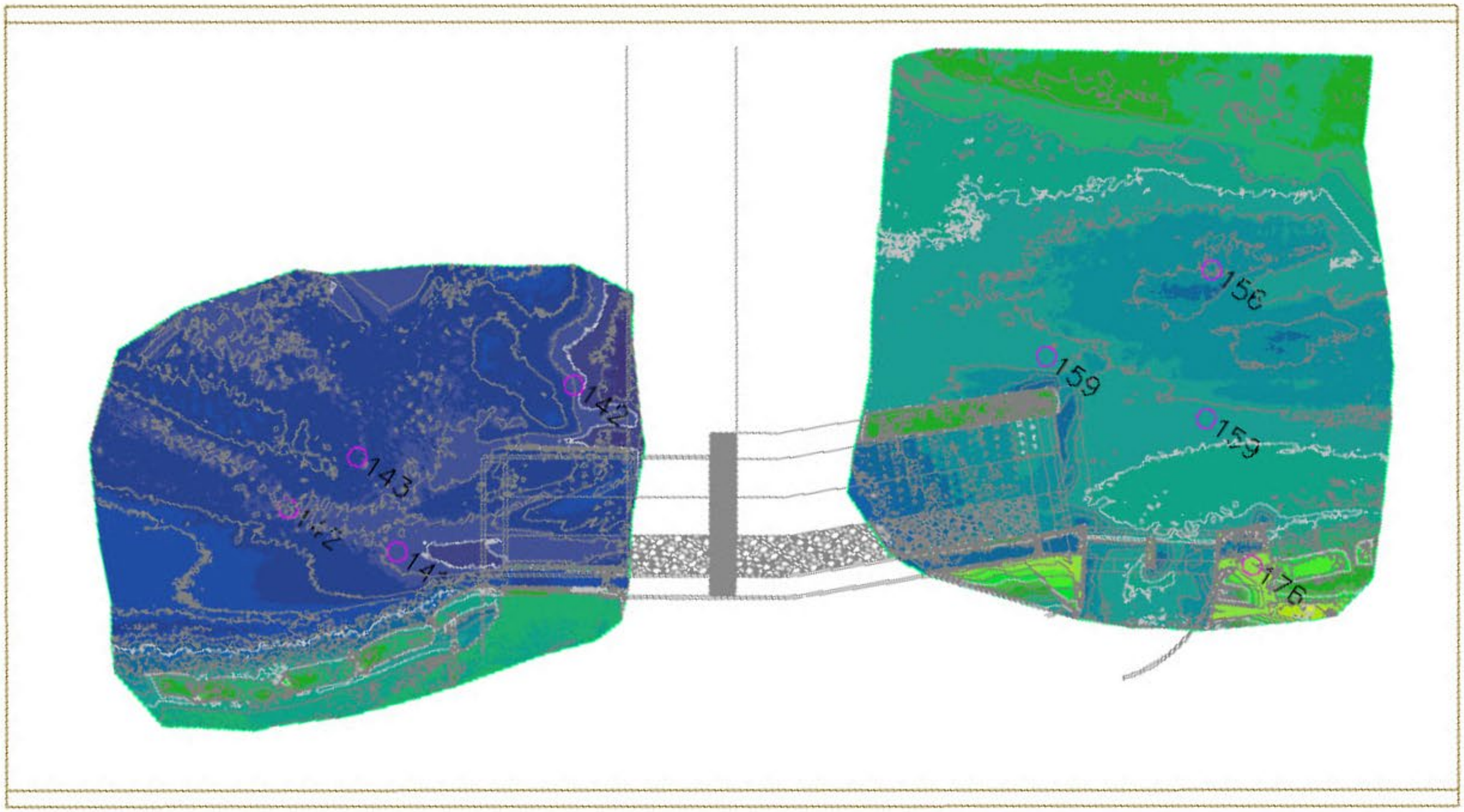


Figure B-87. Elevation contours after model run for MOD-6 design with flushing channel removed at 12,000 ft^3/s river flow. Flow is from right to left.

Elevations Table

Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

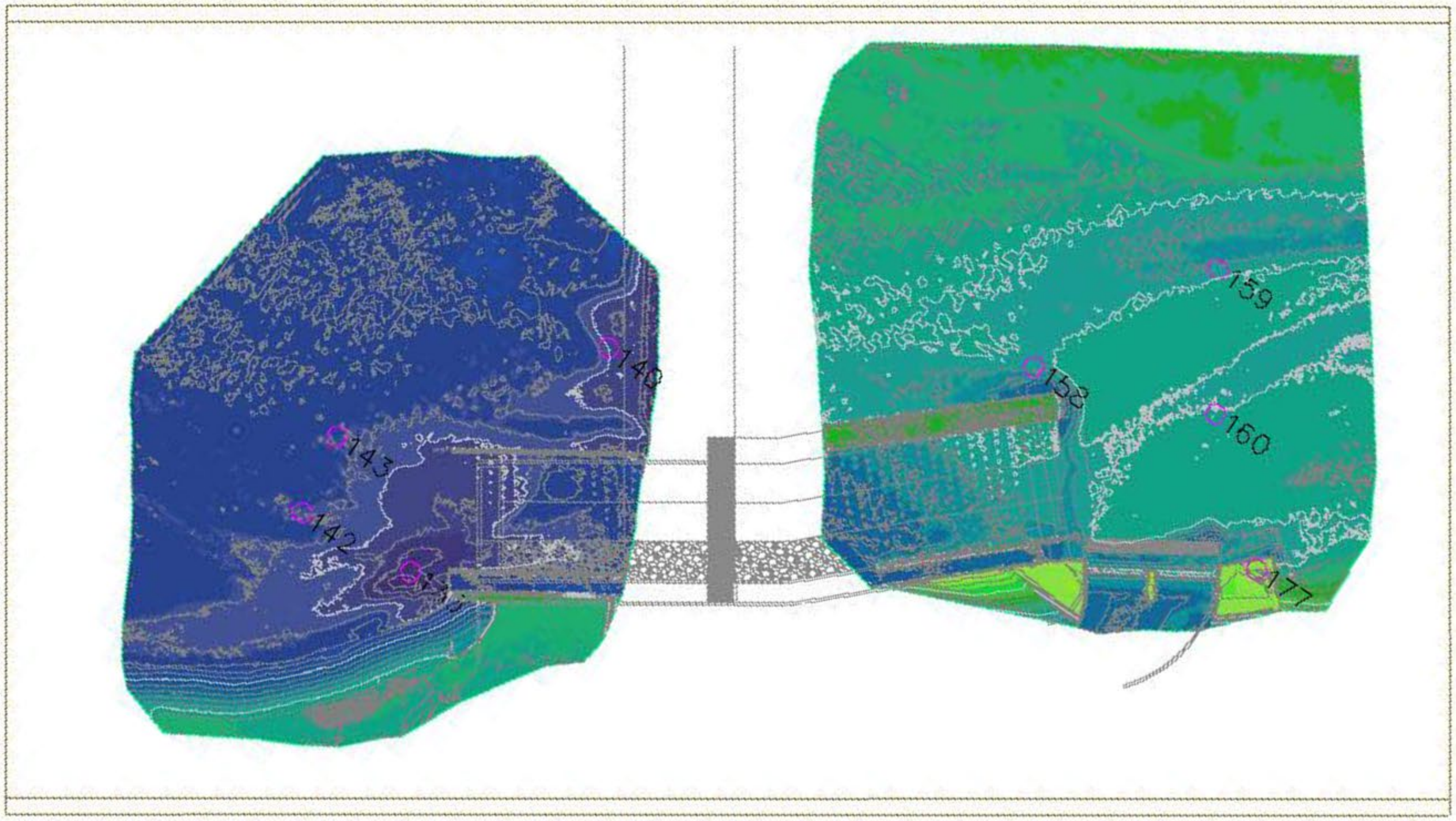


Figure B-88. Elevation contours after model run for MOD-9 design with flushing channel closed at 12,000 ft^3/s river flow. Flow is from right to left.

Elevations Table

Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

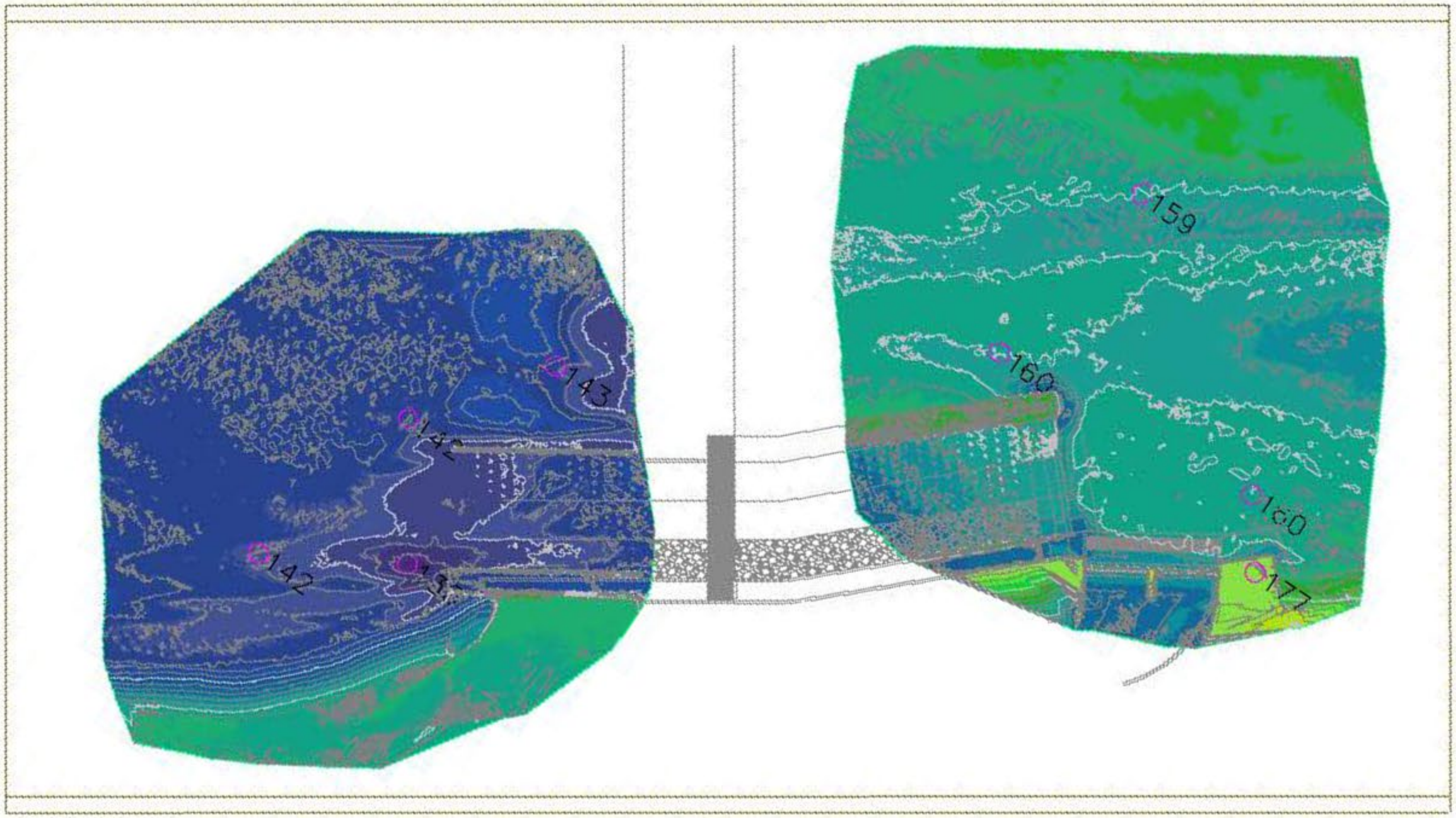


Figure B-89. Elevation contours after model run for MOD-9 design with flushing channel open at 12,000 ft^3/s river flow. Flow is from right to left.

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

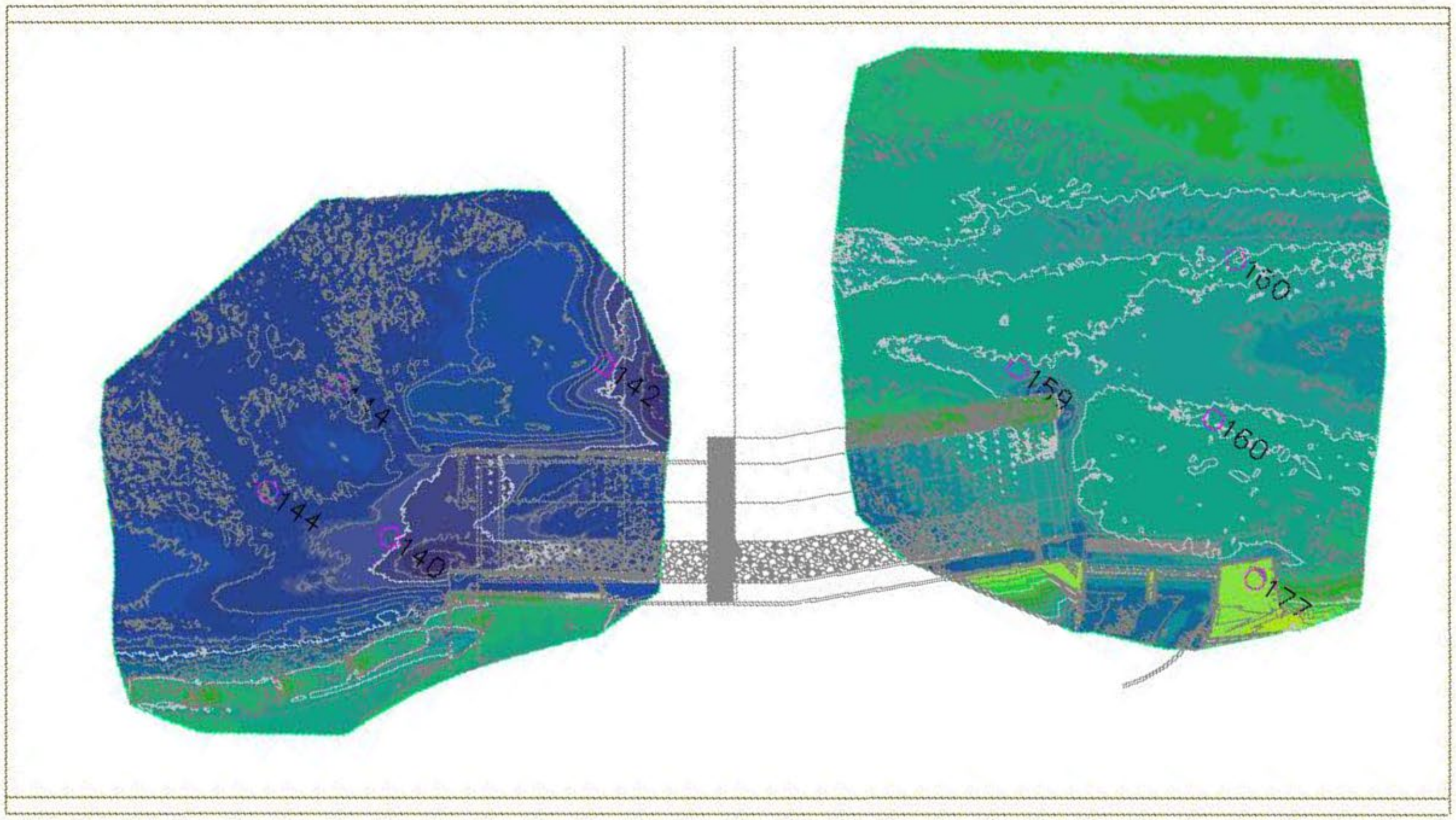


Figure B-90. Elevation contours after model run for MOD-9 design with flushing channel removed at 12,000 ft^3/s river flow. Flow is from right to left.

River Flow 30,000 ft^3/s

MOD-6 Flushing Channel Closed

At 30,000 ft^3/s, the right and left depositional areas above elevation 168 ft were fully inundated. The flow approached straight into the hardened ramp and dam crest. Sediment accumulated from the diversion intake to left side of bullnose. From the right side of bullnose to left crest of dam, almost all of the coarse and fine sand material was removed, exposing larger rock material. The upstream half of the hardened ramp was cleared of most sediment due to scour around the bullnose and flushing channel wall.

Downstream of the dam stilling basin, a significant amount of sediment deposited in a semi-circular pattern. This sediment deposited around the right wall downstream of the hardened ramp. On the baffled section of the hardened ramp, sediment deposited in a transverse pattern on the downstream third of the ramp. Scour deposited downstream of the low flow channel to the end of the model.

MOD-6 Flushing Channel Open

Once the flushing channel was opened, sediment in front of intake gate 4 was cleared. Due to the turbulence around the flushing channel wall, no significant amount of sediment accumulated on the hardened ramp, including the low flow channel.

On the downstream quarter of the hardened ramp, the baffles and low flow channel were partially covered in sediment. Some scour was observed downstream of the low flow channel and the flushing channel.

MOD-6 Flushing Channel Removed

At 30,000 ft^3/s, the right and left depositional areas were completely inundated by flow while portions of elevation 168 ft remained dry on the right side. Most intake gates had sediment deposition up to the top of the gates except for gate 4 which was partially cleared on the sill due to scour around the upstream left wall of the hardened ramp. Sediment deposited in front of the low flow channel and on the apron except for what was cleared by scour around the bullnose.

Nearly half of the downstream baffled portion of the hardened ramp was covered by a transverse deposition of sediment from the shear zone off the angle of the right wall. The sediment deposition pattern continued down the ramp to the end of the model except for a recirculation zone as flow exited the left wall of the hardened ramp. The recirculation zone cleared sand-sized materials immediately downstream end of the low flow channel along the left bank.

MOD-9 Flushing Channel Closed

At 30,000 ft^3/s, the upstream left depositional area was entirely inundated, and the right depositional area was inundated to elevation 168 ft except for a small portion upstream which may have been due to flow separation from the headbox at this large discharge. The main channel continued to shift left, with sediment deposited on the left hardened topography. At the hardened ramp, sediment accumulated at the upstream end of the low flow section. The rest of the hardened ramp apron remained clear of sediment due to scour around the bullnose and flushing channel wall. Sediment accumulated up to the top, and partially covered, intake gates 1, 2, and 3 with the sill around gate 4 and the flushing channel entrance remaining clear due to recirculation around the walls.

The downstream third of the hardened ramp was entirely covered in sediment in a transverse pattern from the separation zone off the right wall angle. Sediment deposition from the dam stilling basin nearly reached the top of the hardened ramp right wall. Flow surges from the hydraulic jump downstream of the dam would frequently overtop the right downstream ramp wall and pass into the hardened ramp. Some scour was observed downstream of the low flow channel.

MOD-9 Flushing Channel Open

After the flushing channel was opened, the sediment level in front of the intake gates dropped slightly such that gates 1-2 were no longer overtopped. However, no significant sediment was cleared from in front of the intake gates. In front of the hardened ramp, sediment deposited near the low flow channel was removed.

On the downstream third of the hardened ramp, the baffles and low flow channel were partially covered in sediment. Some scour was observed downstream of the low flow channel and the flushing channel.

MOD-9 Flushing Channel Removed

Similar to the MOD-9 configuration with the flushing channel closed, the main river channel shifted left, with sediment deposited on the left hardened topography. At the hardened ramp, sediment accumulated at the upstream end of the low flow channel. The rest of the hardened ramp apron remained clear of sediment due to scour around the bullnose and flushing channel wall. Sediment accumulated up to the top intake gates 1 and 2 and partially up gate 3. The sill around gate 4 remained clear due to recirculation around the upstream left wall of the hardened ramp.

There was some sediment deposition along the downstream right side of the hardened ramp. Most of the baffles were not covered by sediment, especially along the wall, due to flow overtopping the ramp wall from the adjacent hydraulic jump formed by the stilling basin.

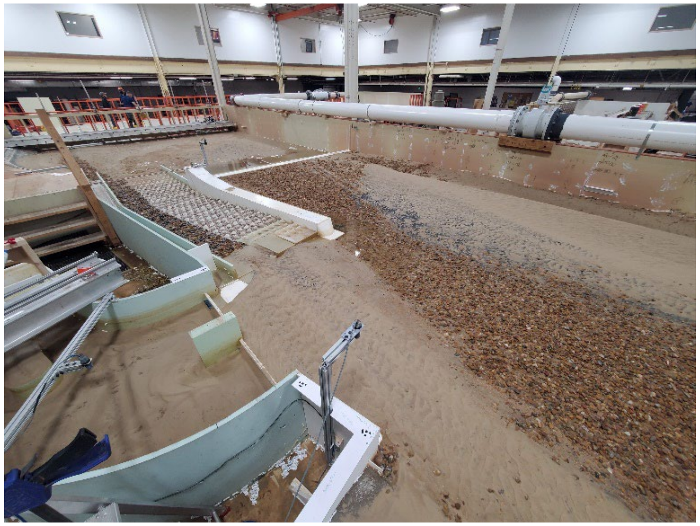


Figure B-91. View looking downstream after dewatering for MOD-6 design with flushing channel closed at 30,000 ft^3/s.

Figure B-92. View looking upstream for MOD-6 design with flushing channel closed after 30,000 ft^3/s flow rate.

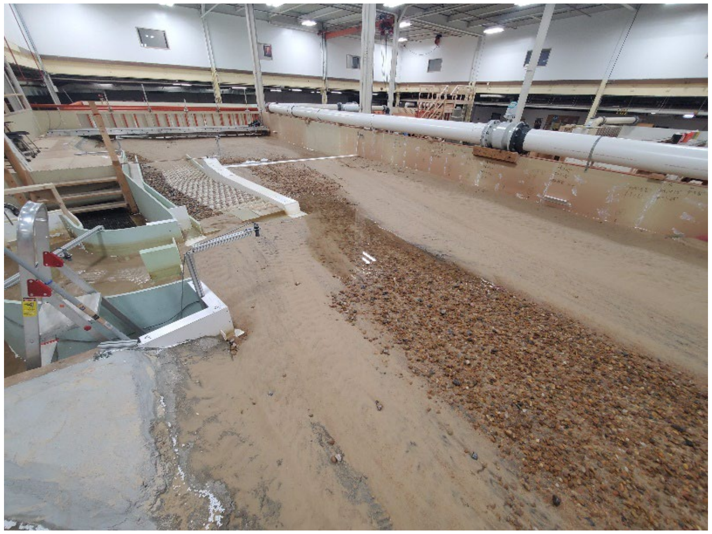


Figure B-93. View looking downstream after dewatering for MOD-9 design with flushing channel closed at 30,000 ft^3/s.

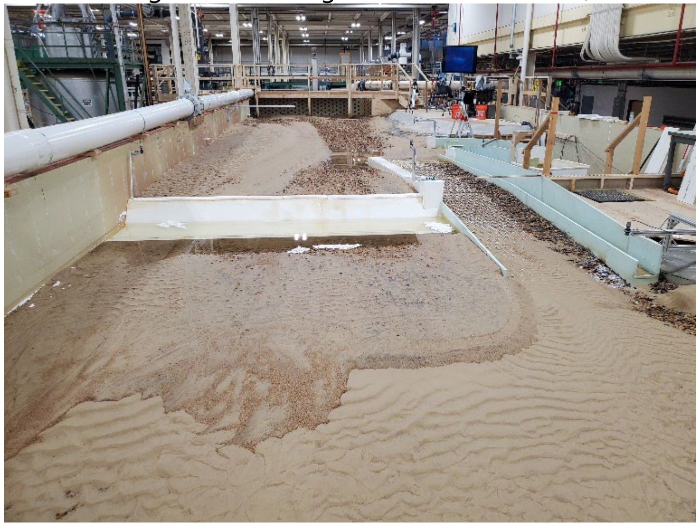


Figure B-94. View looking upstream for MOD-9 design with flushing channel closed after 30,000 ft^3/s flow rate.

Figure B-95. View looking downstream after dewatering for MOD-6 design with flushing channel open at 30,000 ft^3/s.

Figure B-96. View looking upstream for MOD-6 design with flushing channel open after 30,000 ft^3/s flow rate.

Figure B-97. View looking downstream after dewatering for MOD-9 design with flushing channel open at 30,000 ft^3/s.

Figure B-98. View looking upstream for MOD-9 design with flushing channel open after 30,000 ft^3/s flow rate.

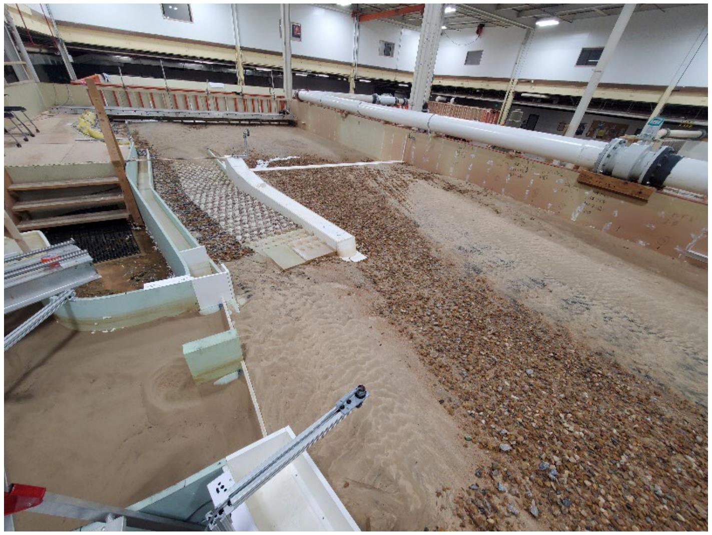


Figure B-99. View looking downstream after dewatering for MOD-6 design with flushing channel removed at 30,000 ft^3/s.


Figure B-100. View looking upstream for MOD-6 design with flushing channel removed after 30,000 ft^3/s flow rate.


Figure B-101. View looking downstream after dewatering for MOD-9 design with flushing channel removed at 30,000 ft^3/s.


Figure B-102. View looking upstream for MOD-9 design with flushing channel removed after 30,000 ft^3/s flow rate.

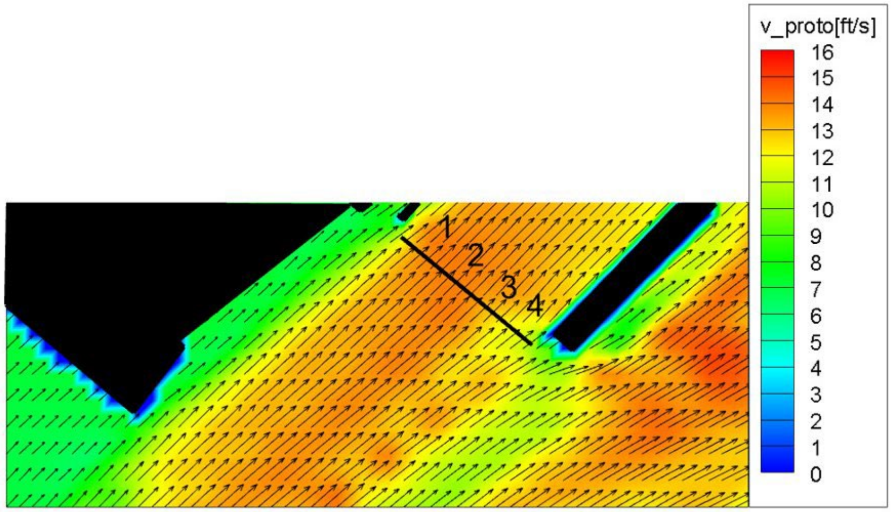


Figure B-103. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-6 design with flushing channel closed at 30,000 ft^3/s river flow.

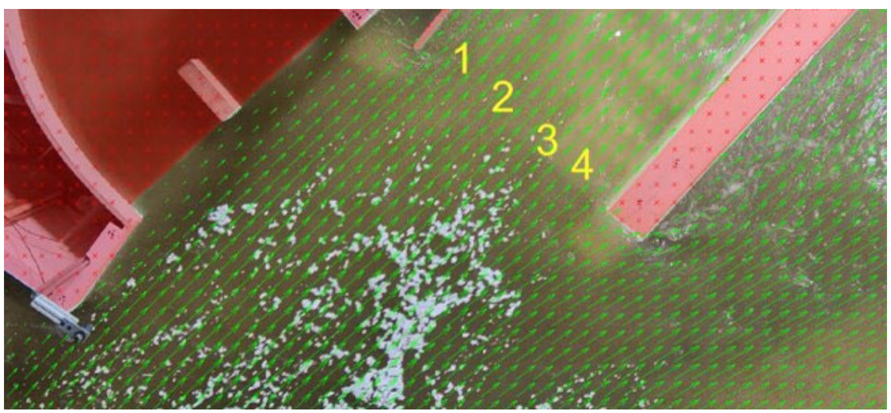


Figure B-104. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-6 design with flushing channel closed at 30,000 ft^3/s river flow.

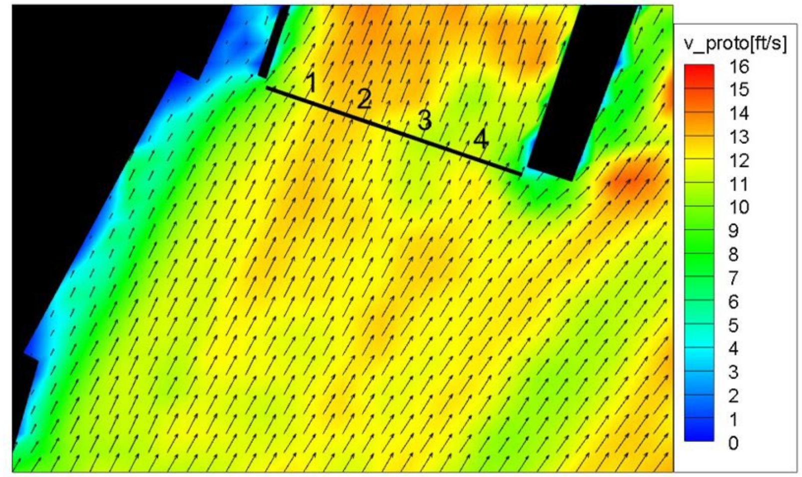


Figure B-105. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-9 design with flushing channel closed at 30,000 ft^3/s river flow.

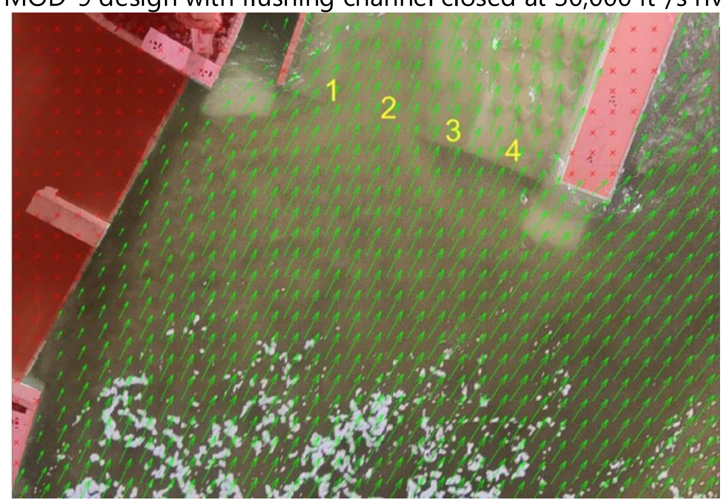


Figure B-106. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-9 design with flushing channel closed at 30,000 ft^3/s river flow.

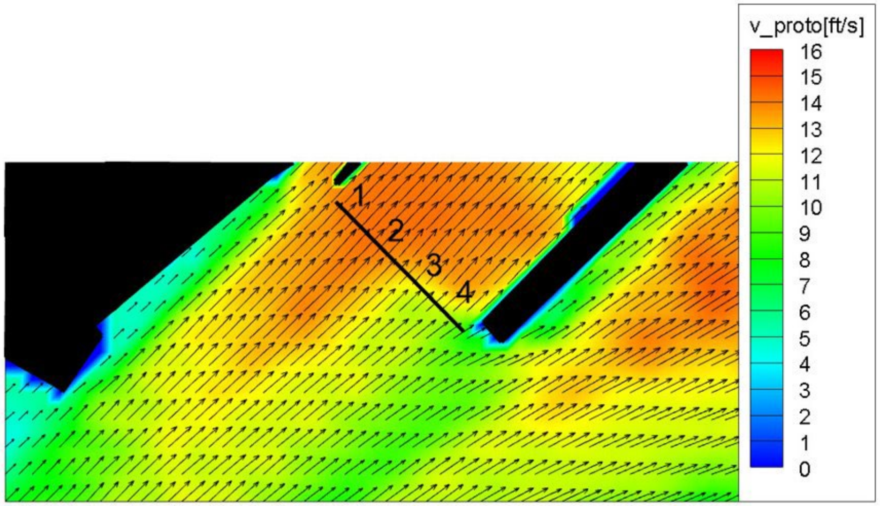


Figure B-107. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-6 design with flushing channel open at 30,000 ft^3/s river flow.

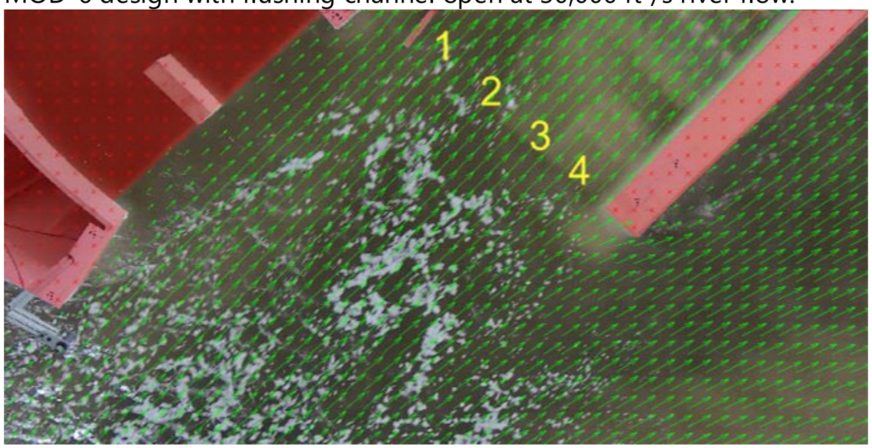


Figure B-108. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-6 design with flushing channel open at 30,000 ft^3/s river flow.

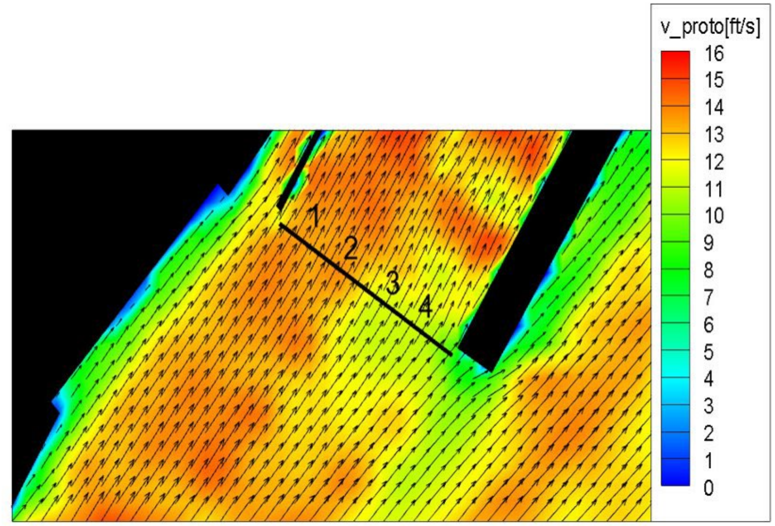


Figure B-109. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-9 design with flushing channel open at 30,000 ft^3/s river flow.

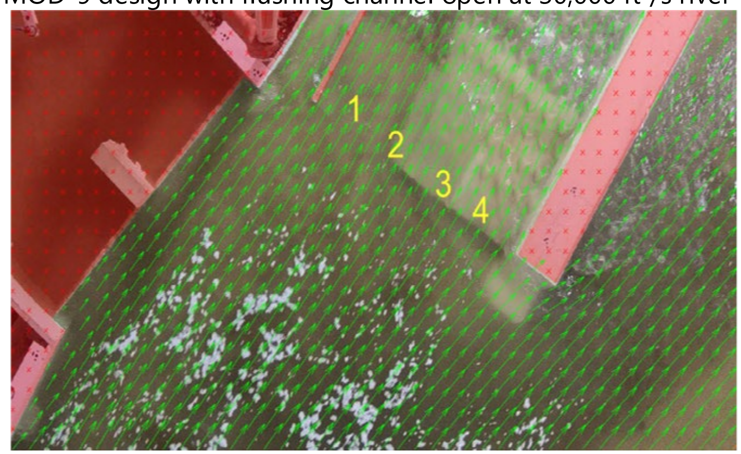


Figure B-110. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-9 design with flushing channel open at 30,000 ft^3/s river flow.

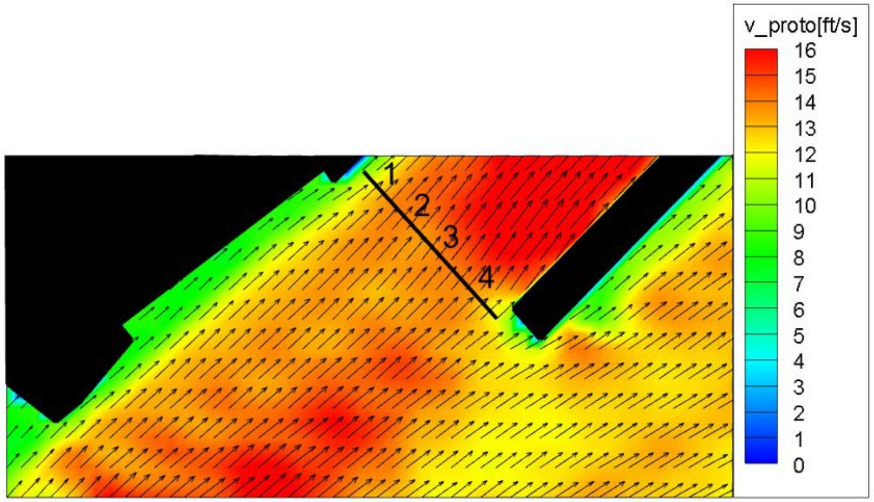


Figure B-111. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-6 design with flushing channel removed at 30,000 ft^3/s river flow.

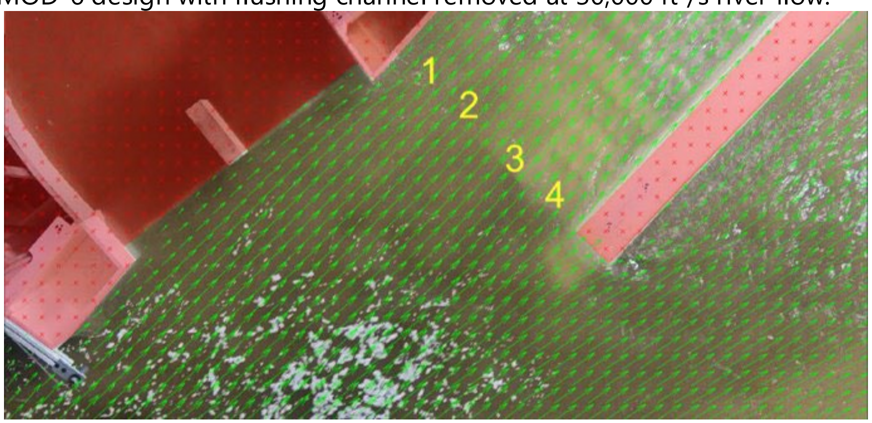


Figure B-112. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-6 design with flushing channel removed at 30,000 ft^3/s river flow.

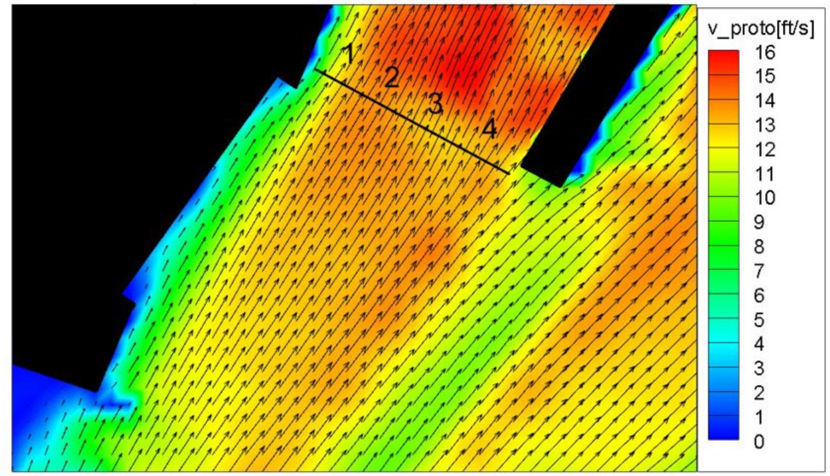


Figure B-113. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-9 design with flushing channel removed at 30,000 ft^3/s river flow.

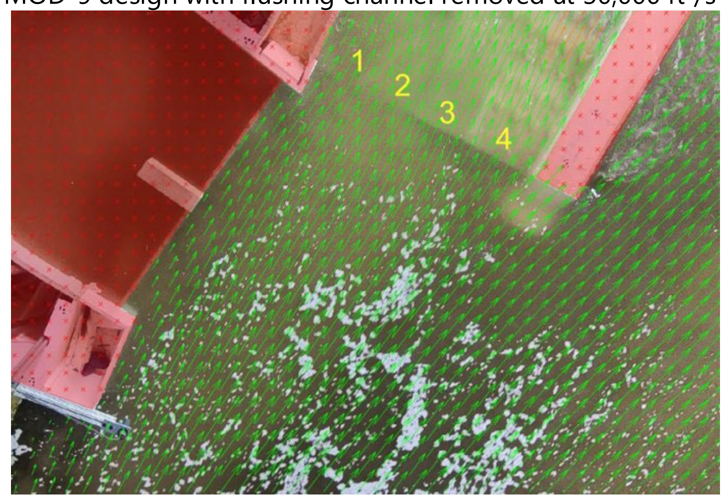


Figure B-114. Surface velocity vector map in area upstream of diversion intake (left) and hardened ramp (right) for MOD-9 design with flushing channel removed at 30,000 ft^3/s river flow.

Table B-10. Average prototype surface velocity magnitudes from LSPIV data at hardened ramp exit at 30,000 ft^3/s. Point "A" and "B" signify the left and right half of the gate, respectively.

	MOD-6 Average Prototype Surface Velocity Magnitude at Hardened Ramp Exit (ft/s)			MOD-9 Average Prototype Surface Velocity Magnitude at Hardened Ramp Exit (ft/s)		
Location	**Flushing Channel Closed**	**Flushing Channel Open**	**Flushing Channel Removed**	**Flushing Channel Closed**	**Flushing Channel Open**	**Flushing Channel Removed**
Gate 1A	11.3	13.9	9.9	9.0	12.2	6.4
Gate 1B	13.6	14.1	13.1	11.6	13.6	12.8
Gate 2A	14.0	14.2	14.0	12.8	13.6	13.7
Gate 2B	14.0	13.8	13.6	12.2	13.1	13.4
Gate 3A	13.7	12.7	14.0	11.3	11.5	12.9
Gate 3B	12.8	11.6	14.0	11.2	11.3	12.8
Gate 4A	11.9	11.0	13.3	11.0	10.9	13.1
Gate 4B	10.6	8.8	11.8	6.1	8.9	12.2

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

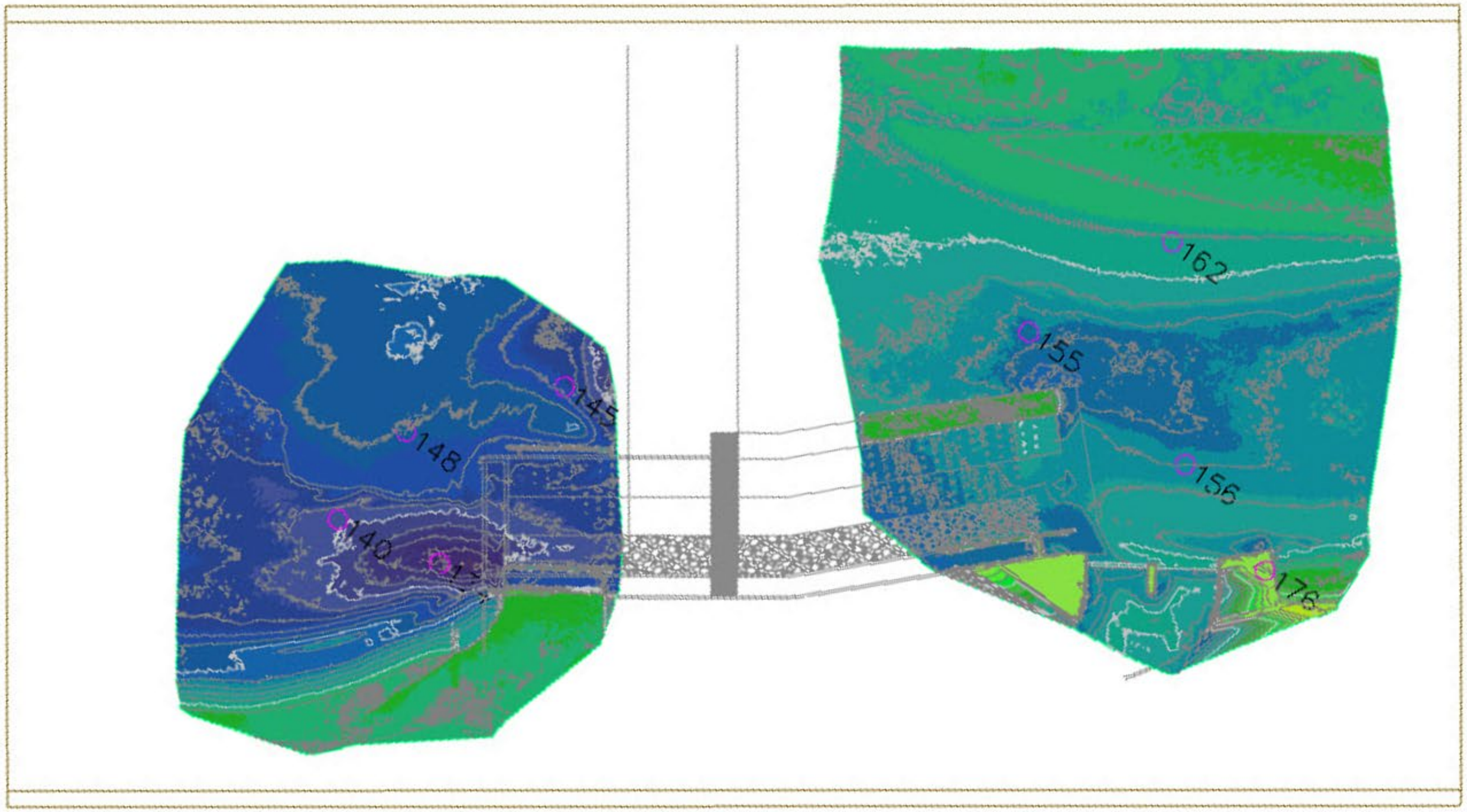


Figure B-115. Elevation contours after model run for MOD-6 design with flushing channel closed at 30,000 ft^3/s river flow. Flow is from right to left.

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

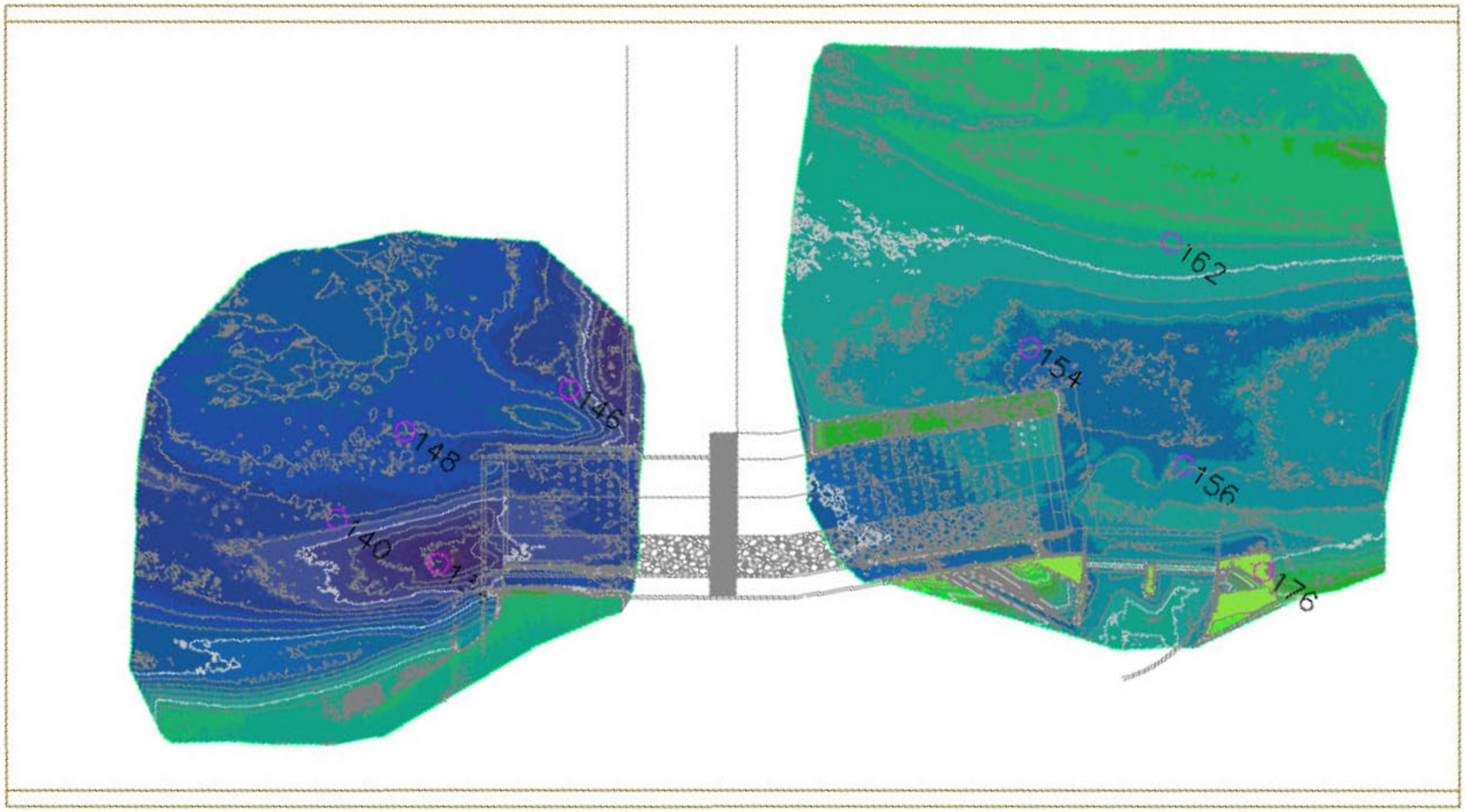


Figure B-116. Elevation contours after model run for MOD-6 design with flushing channel open at 30,000 ft^3/s river flow. Flow is from right to left.

Elevations Table

Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

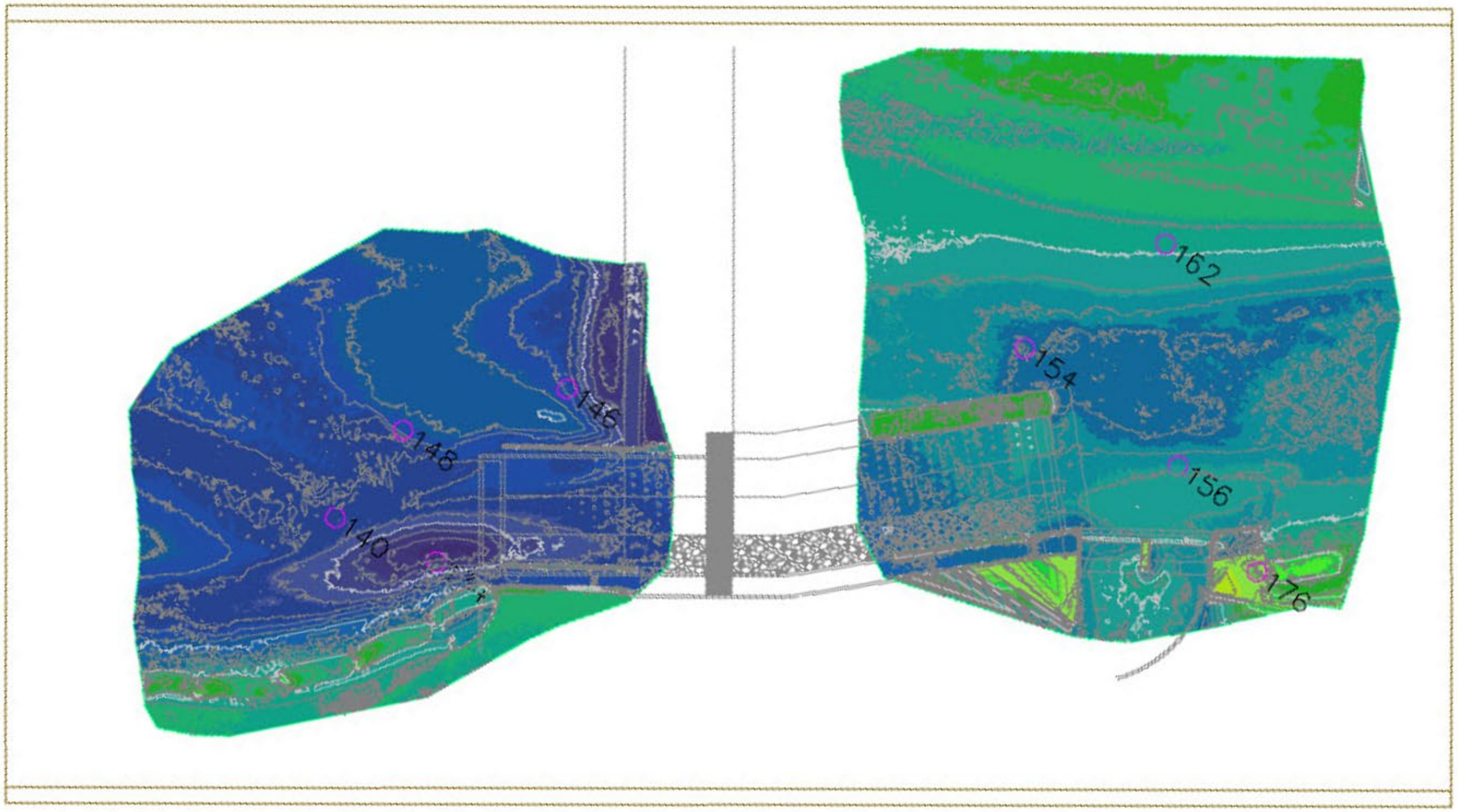


Figure B-117. Elevation contours after model run for MOD-6 design with flushing channel removed at 30,000 ft^3/s river flow. Flow is from right to left.

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

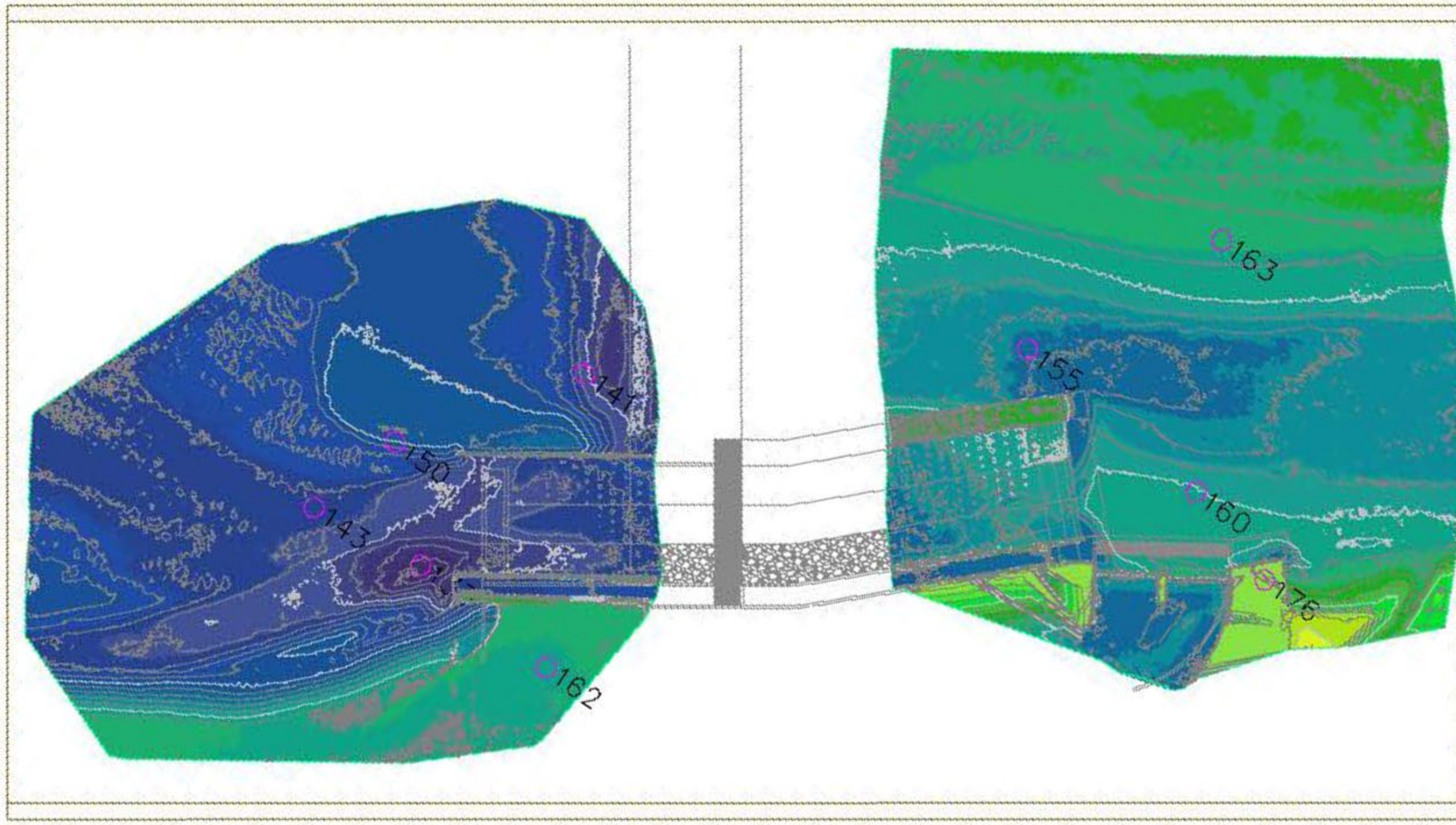


Figure B-118. Elevation contours after model run for MOD-9 design with flushing channel closed at 30,000 ft^3/s river flow. Flow is from right to left.

Elevations Table

Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

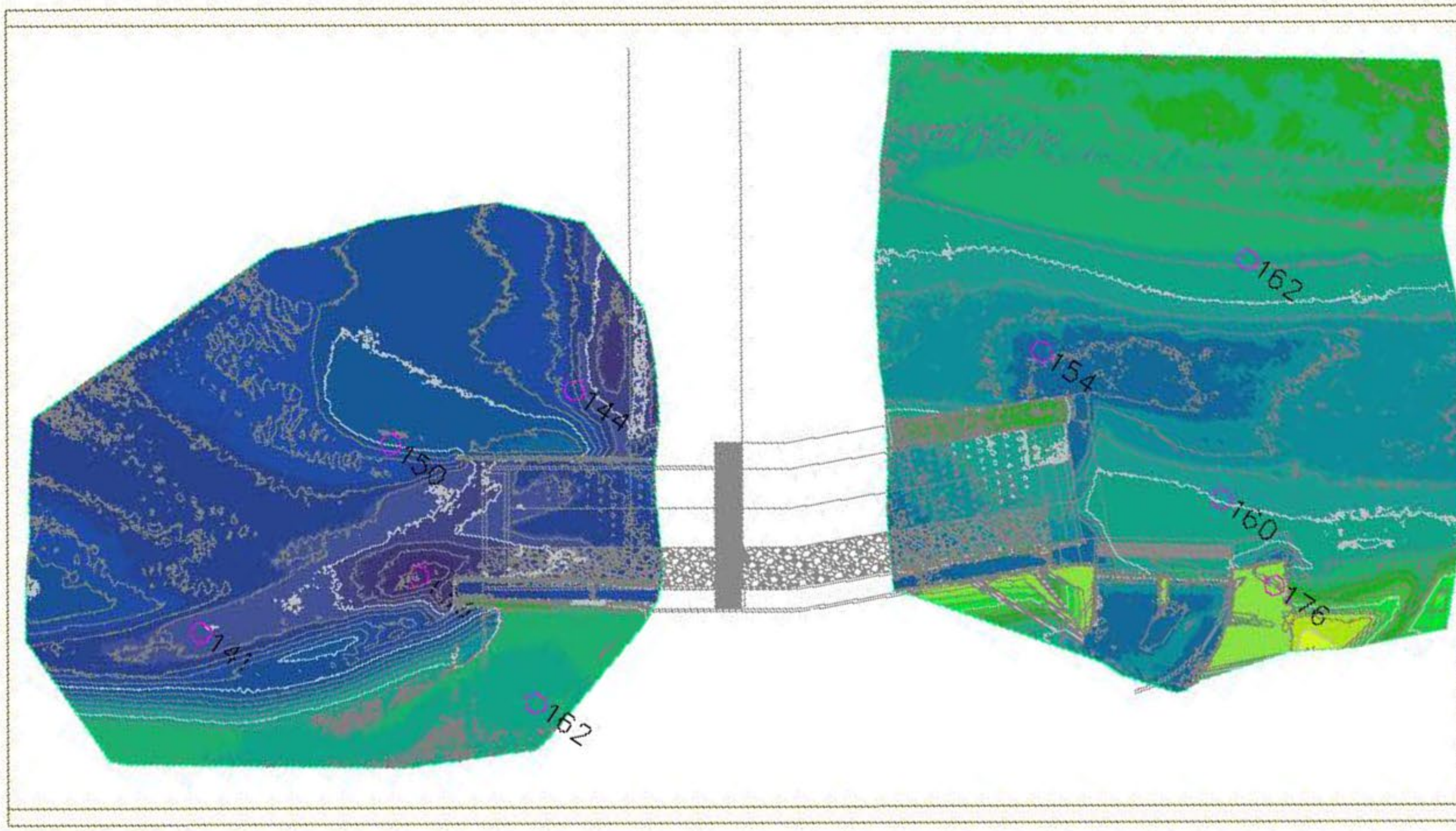


Figure B-119. Elevation contours after model run for MOD-9 design with flushing channel open at 30,000 ft^3/s river flow. Flow is from right to left.

Elevations Table			
Number	Minimum Elevation	Maximum Elevation	Color
1	120.00	122.50	
2	122.50	125.00	
3	125.00	127.50	
4	127.50	130.00	
5	130.00	132.50	
6	132.50	135.00	
7	135.00	137.50	
8	137.50	140.00	
9	140.00	142.50	
10	142.50	145.00	
11	145.00	147.50	
12	147.50	150.00	
13	150.00	152.50	
14	152.50	155.00	
15	155.00	157.50	
16	157.50	160.00	
17	160.00	162.50	
18	162.50	165.00	
19	165.00	167.50	
20	167.50	170.00	
21	170.00	172.50	
22	172.50	175.00	
23	175.00	177.50	
24	177.50	180.00	
25	180.00	182.50	
26	182.50	185.00	
27	185.00	187.50	
28	187.50	190.00	
29	190.00	192.50	
30	192.50	195.00	
31	195.00	197.50	

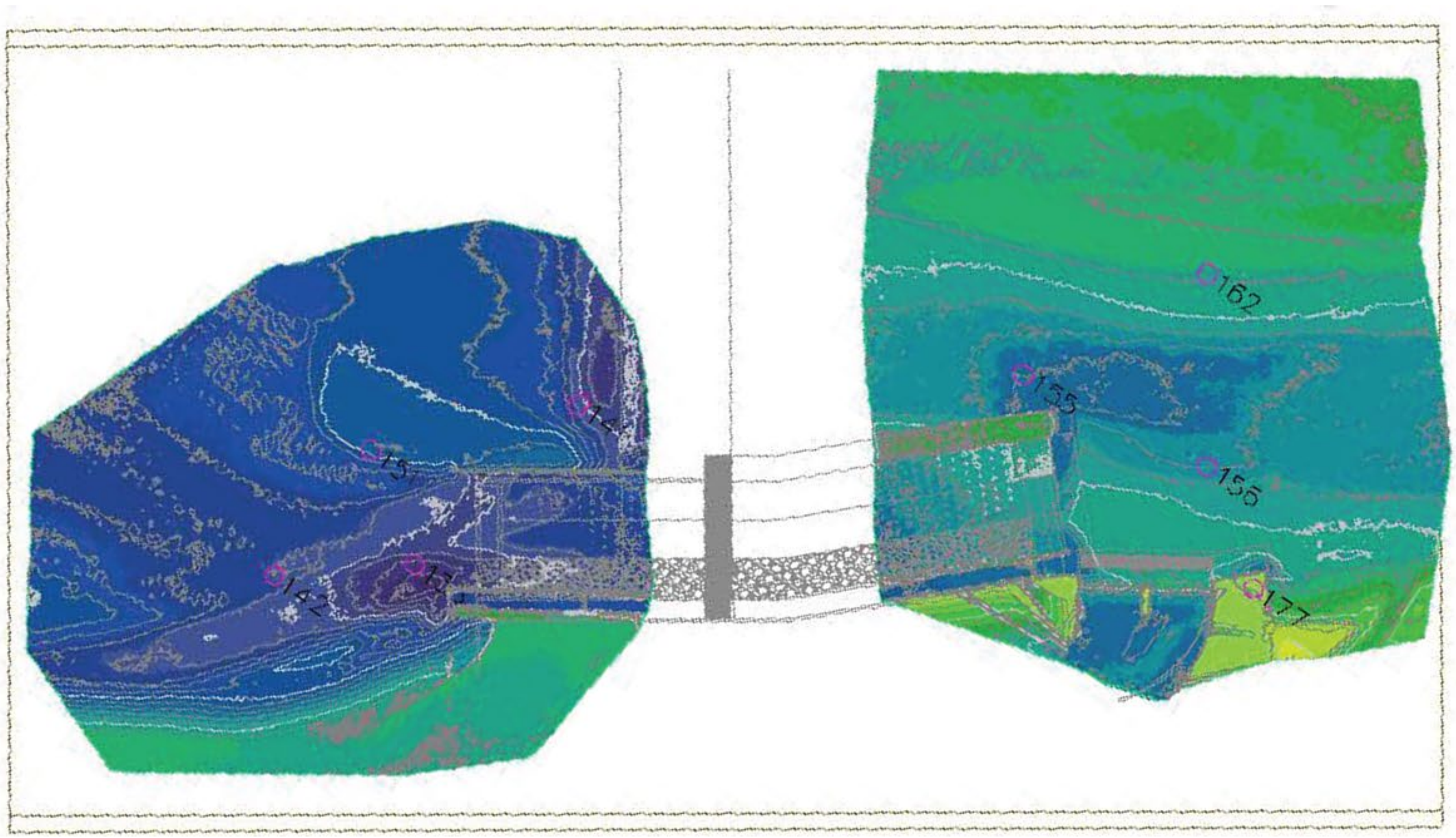


Figure B-120. Elevation contours after model run for MOD-9 design with flushing channel removed at 30,000 ft^3/s river flow. Flow is from right to left.

Comparison of MOD-6 and MOD-9 Design Configurations

Key points summarizing the comparison of MOD-6 and MOD-9 are given below:

- Flow approaching the hardened ramp and diversion intake for flows of 3,000 and 6,000 ft^3/s was generally more channelized in MOD-6. This produced more flow curvature to the left toward the diversion intake and hardened ramp compared to MOD-9 which had a somewhat straighter approach to these structures due to greater water levels above the baseline channel topography. There was significant flow separation from the bullnose on the ramp wall into the hardened ramp for every configuration that was tested. Approach flow patterns for both design configurations became more similar with increased discharge as more of the river channel was utilized which allowed a more linear approach to the hardened ramp. Surface velocity results showed slightly higher velocities for MOD-6 which is to be expected with lower water depths compared to MOD-9.
- Flow patterns at the downstream end of the hardened ramp were very similar for both configurations over the range of discharges tested. In general, flow exiting the ramp paralleled the topography of the left bank and dispersed uniformly as it moved downstream. Subsequent sediment bedforms downstream were similar overall with no extreme localized scour or deposition features.
- Some differences were seen in flow and deposition patterns in the baffled section near the downstream end of the ramp. For MOD-9 a shear zone formed off the right wall about midway down the ramp where it angles to the right. This produced a low velocity region downstream along the right side of the ramp where sediment deposition naturally occurred. Deposition in this area also occurred for MOD-6 although specific patterns and locations were different. These differences are not considered to be significant and may be due to differences in upstream flow patterns approaching the hardened ramp.
- The main difference observed in MOD-6 and MOD-9 was the significant reduction in sediment deposited immediately upstream of the diversion intake and hardened ramp exit for MOD-9. This was most likely caused by changes to the sediment load carrying capacity of the flow between MOD-6 and MOD-9 over the same time duration. Extending the run time duration for MOD-9 will likely yield very similar sediment results to MOD-6 as discussed in the next section.

MOD-6 and MOD-9 Test Duration and Quasi-steady state

By raising the hardened ramp and the dam crest for the MOD-9 design, the upstream flow depth was increased which naturally decreased channel velocities and slope of the water surface for the same discharge. Test durations were kept the same as those for MOD-6 to maintain consistency. However, review of the results showed that the MOD-9 test durations should have been increased to allow sufficient time for the bedforms to reach equilibrium. These test runs were not repeated due to schedule constraints but test durations in the 1:12 model will be adjusted based on this finding to ensure both MOD-6 and MOD-9 can be directly compared.

In addition, a trial run with an extended duration at 6,000 ft^3/s with flushing channel closed and diverting 800 ft^3/s was completed to see if the bed form continued to progress downstream like that seen with MOD-6. This trial had different initial bed conditions than the baseline runs but visually reached equilibrium within 6.5 hours and caused deposition on the diversion gates and on the upstream end of the hardened ramp very similar to the MOD-6 baseline runs (Figure B-121 to Figure B-123).

Figure B-121. MOD-6 flushing channel closed at 6,000 ft^3/s after a 2 hr run duration.

Figure B-122. MOD-9 flushing channel closed at 6,000 ft^3/s after a 2 hr run duration.

Figure B-123. MOD-9 flushing channel closed at 6,000 ft^3/s after a 6.5 hr run duration.

To balance changes in flow depth and velocity the sediment load capacity of the flow must decrease. This is shown in Eq. 1 below where g_s is the unit discharge of sediment (metric tons/meter/second) which was estimated for MOD-6 and MOD-9 for flows up to 12,000 ft^3/s. While this is only an estimation, Figure B-124 shows the general trend of reduced load carrying capacity of MOD-9 which is likely the cause of less sediment deposition near the intake and hardened ramp over the same test period as MOD-6.

$$\left(\frac{k_r}{k'_r}\right)^{\frac{3}{2}} r_b S = 0.047(\gamma_s - \gamma)d_m + 0.25\left(\frac{\gamma}{g}\right)^{\frac{1}{3}}\left(\frac{\gamma_s - \gamma}{\gamma_s}\right)^{\frac{2}{3}} g_s^{\frac{2}{3}} \qquad \text{Eq. 1}$$

Where:

k_r = roughness coefficient = 1/n where n = Manning's roughness coefficient; Manning's n can be estimated by Strickler's equation as given by Laursen (1963): n = 0.041 $d_m^{1/6}$

k'_r = 26/($d_{90}^{1/6}$) where d_{90} is in meters (estimated from scaled gradation of 1:24 model material)

γ = specific weight of water (metric tons/cubic meter)

γ_s = specific weight of sediment (metric tons/cubic meter)

r_b = hydraulic radius in meters (approximately equal to depth for wide channel)

S = slope (estimated from 2D HEC-RAS water surface results for 800 ft upstream of ramp)

d_m = effective sediment diameter in meters (= $S_i p_i d_{si}$ where p_i = percent by weight of size d_{si} - estimated from scaled gradation of 1:24 model material)

g = gravitational constant

g_s = bed load (metric tons/meter/second)

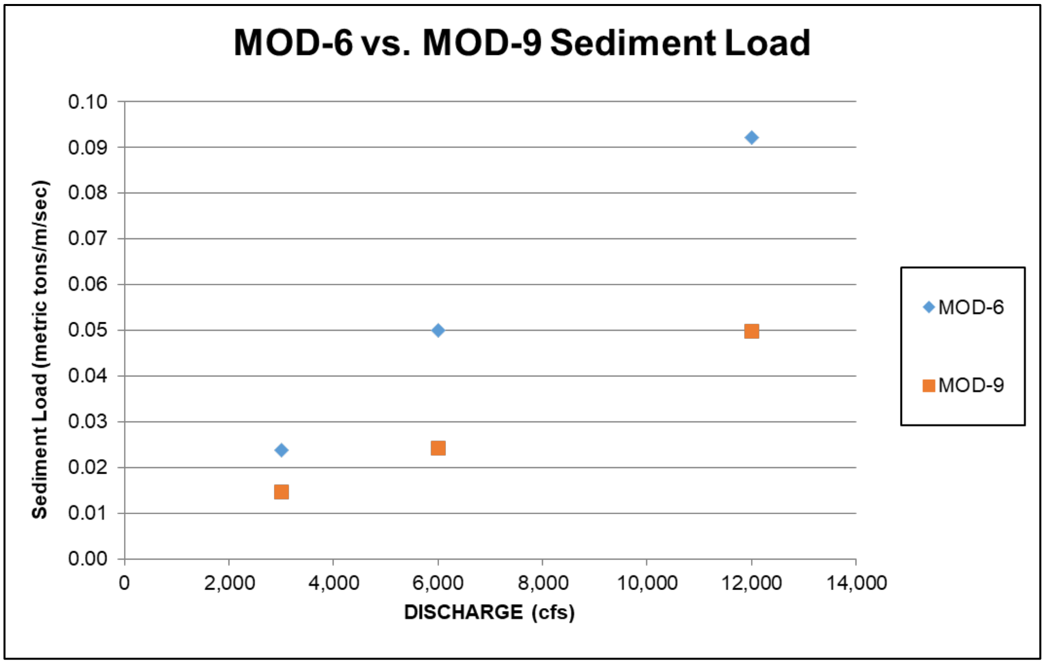


Figure B-124. Comparison of sediment load carrying capacity at 3,000 ft^3/s, 6,000 ft^3/s, and 12,000 ft^3/s.

Appendix B-1: Detailed Physical Model Observations

Table B-11. Model observations for MOD-6 design with flushing channel closed, open, and removed at 3,000 ft^3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-6 Flushing Channel Closed**	• Left bank elevation 162 ft overtopped except for a sand bar formation at downstream left, which caused the flow to fork slightly. Right bank only partially submerged at elevation 162 ft. • Right half of dam crest was dry. The right bank was dry as well, interfering with water surface elevation reading.
	MOD-6 Flushing Channel Open	• Shallow sheet flow overtopped majority of left bank elevation 162 ft, except at left edge near topography. • Under the flow, sediment accrued to form a submerged sand bar with a slight fork still visible from flushing channel closed trial. • Approximately half of the dam crest was utilized for flow, the right half and bank remained dry.
	MOD-6 Flushing Channel Removed	• Left bank elevation overtopped at elevation 162 ft, except for a sand bar at lower portion of topography. Sand bar in this trial more pronounced than other upstream MOD-6 conditions • Right bank elevation 162 ft overtopped to 288 ft upstream of the dam. • Right dam crest was dry from slightly past halfway point.
Upstream of Hardened Ramp & Flushing Channel	**MOD-6 Flushing Channel Closed**	• Sediment accumulated in front of low flow channel. Entire hardened ramp apron covered by sediment. • Bullnose caused flow split with recirculating eddy and some scour on right side • As water entered and recirculated in the flushing channel entrance, sediment would accumulate.
	MOD-6 Flushing Channel Open	• Right side of fork described in upstream river conditions diverted flow towards bullnose, which continued to scour on right side. • Sharp bend of water around hardened ramp into flushing channel caused scour upstream of ramp. Nearly all of hardened ramp apron remained clear of sediment except one area in front of diversion intake gate 2 where the flow coming around bend of the flushing channel and bullnose created deposition zone.
	MOD-6 Flushing Channel Removed	• Sediment accumulated in front of hardened ramp from end of left bank to low flow channel. • Sediment prevented from accumulating in front of other hardened ramp gates by scour from bullnose and intake edge, in a pattern similar to MOD-6 with flushing channel open. • Bullnose caused flow split with recirculating eddy and some scour on right side.
Upstream of Diversion Intake	**MOD-6 Flushing Channel Closed**	• Sediment accumulated in front and behind of all intake gates. Additionally, sediment overtopped gate 2 for portion of trial. • A large sand bar formed in front of intakes gates 2-4, which increased flow passing over the gates and into the intake.
	MOD-6 Flushing Channel Open	• Left side of fork described in upstream river conditions diverted flow into intake gates 1-2. • Sediment piled on upstream side of intake gates 1-3. Intake gate 4 was cleared of sediment to the apron due to turbulence around flushing channel.

Location	Configuration	Observations
	MOD-6 Flushing Channel Removed	• Sediment accumulated in front of hardened ramp from end of left bank to intake gate 3. Gate 3 was eventually entirely overtopped by sediment, which continued into the intake. • Area in front of intake gates 3-4 have sediment overtopping the sill and up to the front of the gate. In front of intake gates 1-2, there is an area of no sediment deposition. The sill and apron remained relatively clear of sediment throughout the entire trial.
Inside Diversion Intake	**MOD-6 Flushing Channel Closed**	• Immediately behind the gates, hydraulic jump caused by the gates prevented any sediment from accumulating. Downstream of the pier, sediment accumulated in a uniform pattern to the end of the intake.
	MOD-6 Flushing Channel Open	• Immediately behind the gates, hydraulic jump caused by the gates prevented any sediment from accumulating. Downstream of the pier, sediment accumulated in a uniform pattern to the end of the intake.
	MOD-6 Flushing Channel Removed	• Sediment accumulated immediately behind intake gates 2-4, with nearly all the canal filled with sediment. This was different from previous trials where sediment was unable to accumulate immediately behind gates. Sediment did not accumulate behind intake gate 1, as seen in the previous MOD-6 configurations.
Downstream of Hardened Ramp & Flushing Channel	**MOD-6 Flushing Channel Closed**	• Small scour hole developed downstream of low flow channel at entrance. • Sediment accumulated in between baffles in lower quarter of ramp, however the baffles are not fully covered and still impacted the flow. • Flow down the ramp remained supercritical until the last 3-4 rows of baffles.
	MOD-6 Flushing Channel Open	• Scour hole observed downstream of flushing channel. • Sediment accumulated in between baffles for lower quarter of ramp, about the same as previous trials. Last 6 rows of baffles under subcritical flow, with bottom 3 rows barely visible. • Transverse waves occurred in flushing channel downstream of bend in channel.
	MOD-6 Flushing Channel Removed	• No significant scour observed downstream of hardened ramp. • Sediment accumulated in between baffles for lower quarter of ramp, about the same as previous trials. Last 6 rows of baffles under subcritical flow, with bottom 3 rows barely visible.
Downstream of Dam	**MOD-6 Flushing Channel Closed**	• Sediment accumulated immediately after the dam stilling basin and the hardened ramp.
	MOD-6 Flushing Channel Open	• Sediment accumulated immediately after the dam stilling basin and the hardened ramp. A ripple pattern was seen in the sediment deposition downstream of flushing channel.
	MOD-6 Flushing Channel Removed	• Sediment accumulated immediately after the dam stilling basin and the hardened ramp. A ripple pattern was seen in the sediment deposition patterns after end of low flow channel.

Table B-12. Model observations for MOD-9 design with flushing channel closed, open, and removed at 3,000 ft^3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-9 Flushing Channel Closed**	• Left bank elevation 162 ft completely overtopped with some flow at elevation 164 ft around 960 ft upstream of the dam. Right bank elevation 162 ft was completely overtopped and elevation 164 ft partially overtopped through approximately 576 ft upstream of the dam. • Dam crest was spilling water mainly through lowered left notch with some spillover onto center-left of dam.
	MOD-9 Flushing Channel Open	• Left bank partially overtopped at elevation 162 ft and sand bar in middle of topography exposed. Right bank elevation 162 ft submerged until about 384 ft upstream of the dam • Left crest notch fully utilized with some overflow; less than half of the crest was utilized with right side completely dry.
	MOD-9 Flushing Channel Removed	• Left bank elevation 162 ft almost immediately overtopped with portion of 164 ft overtopped. Right bank elevation 162 ft no longer defined from channel bed up to about 288 ft upstream of the dam with elevation 164 ft entirely intact. • Flow over dam concentrated around lowered left notch; right bank not active except for overflow from left.
Upstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• Sediment in front of hardened ramp accumulated at about elevation 162 ft. This formed one cohesive sand bar with sheet flow over it from left bank to dam crest. • Some scour was still seen around the bullnose. However, it was significantly less than MOD-6, with no scour hole forming. • Low flow channel sill filled with sediment. The rest of the sill and apron did not have sediment deposition.
	MOD-9 Flushing Channel Open	• Sediment in front of hardened ramp accumulated at about elevation 162 ft. This formed one cohesive sand bar with sheet flow over it from left bank to dam crest (similar to MOD-9 flushing channel closed). However, this extended in front of the flushing channel entrance. • No new scour in front of bullnose. There was still an eddy around the right side but weaker than MOD-6.
	MOD-9 Flushing Channel Removed	• Sediment washed away from right bank and channel moving as submerged bedform to low flow channel section of the hardened ramp, where the sediment deposited in front of low flow channel • Scour in front of bullnose with recirculating eddy more significant with flushing channel open/closed in MOD-9.
Upstream of Diversion Intake	**MOD-9 Flushing Channel Closed**	• End of left bank closest to canal remained intact, even though it was overtopped. The area in front of intake gates to hardened ramp gate 2 had no sediment deposition. • Slight scour hole under apron in front of intake gate 1. • The apron in front of intake gates 3-4 was partially covered by sediment; no sediment accumulated on the sill in front of any of the intakes.
	MOD-9 Flushing Channel Open	• No new sediment deposited from left topography edge to front of intake gates 1-2. Similar to MOD-9 flushing channel closed. • Slight scour hole under apron in front of intake gate 1. • All of canal apron and sill exposed.
	MOD-9 Flushing Channel Removed	• Section in front of intake still at original topography with sediment building up parallel to hardened ramp. Some sediment on apron level with original topography but no sediment on gates themselves. Similar to MOD-9 flushing channel closed. • Slight scour hole under apron in front of intake gate 1. • Sill in front of intake gates 2-3 partially covered by sediment. Apron had some sediment deposition, but mostly still exposed.

Location	Configuration	Observations
Inside Diversion Intake	**MOD-9 Flushing Channel Closed**	• Some scour around canal pier. However, there was not any significant sediment deposition in the intake.
	MOD-9 Flushing Channel Open	• Little sediment deposit in the canal, similar to MOD-9 flushing channel closed.
	MOD-9 Flushing Channel Removed	• No sediment immediately behind intake gates 1-2, some accrued behind gates 3-4. • Sediment accumulated in the intake, similar to MOD-6, unlike MOD-9 flushing closed/open.
Downstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• MOD-9 baffle extension and 5 additional baffled rows were fully covered in sediment up to the very top of the baffle. Area was also in subcritical flow, with water on top minimally influenced by baffles. • Scour pattern downstream of low flow channel continued to end of model.
	MOD-9 Flushing Channel Open	• Sediment accumulating on baffles of hardened ramp past MOD-9 insert, similar to MOD-9 flushing channel closed. • Transverse wave as seen in MOD-6 appeared again, with transverse wave starting after bend in channel. • Scour hole formed downstream of flushing channel with recirculating eddy.
	MOD-9 Flushing Channel Removed	• Hardened ramp submerged up past the MOD-9 insert with some sediment accumulating on ramp near site of jump. • Downstream left topography seems to be artificially elevated on left side from topography reset. This did not impact the flow regime but lowered for next trial. • Slight scour hole formed downstream of low flow channel.
Downstream of Dam	**MOD-9 Flushing Channel Closed**	• Sediment accumulated immediately after the dam stilling basin and the hardened ramp. A ripple pattern was seen in the sediment deposition downstream of flushing channel.
	MOD-9 Flushing Channel Open	• Sediment accumulated immediately after the dam stilling basin and the hardened ramp. A ripple pattern was seen in sediment deposition patterns after end of low flow channel. • Scour from flushing channel continued with a rightwards bend to the end of the model. This caused sediment to accrue on left edge of concrete topography.
	MOD-9 Flushing Channel Removed	• Sediment accumulated immediately after the dam stilling basin and the hardened ramp. A ripple pattern was seen in sediment deposition patterns after end of low flow channel. • As flow was pushed more to the right than previous trials due to artificial elevation of topography, significant deposition occurred to the right edge of hardened ramp.

Table B-13. Model observations for MOD-6 design with flushing channel closed, open, and removed at 6,000 ft^3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-6 Flushing Channel Closed**	• Left bank almost entirely overtopped through elevation 164 ft. Portion closest to concrete topography remains exposed. Right bank elevation 164 ft still intact though some water has overtopped portions of it. • Dam crest almost fully active with some flow movement throughout crest.
	MOD-6 Flushing Channel Open	• Left bank almost entirely overtopped through elevation 164 ft. Right bank elevation 164 ft still intact though some water has overtopped portions of it, becomes dry again from about 288 ft upstream of the dam to the dam crest. • Right side of dam crest not utilized due to diversion of flow into flushing channel.
	MOD-6 Flushing Channel Removed	• Left bank sand bar from 3,000 ft^3/s partially overtopped and replaced by sediment at uniform elevation with sheet flow over it from about 672 ft upstream fo the dam to the low flow portion of the hardened ramp. Right bank stable at elevation 164 ft. • Dam crest on right mostly dry with some flow passing over right portion; left side half of dam crest fully utilized.
Upstream of Hardened Ramp	**MOD-6 Flushing Channel Closed**	• Large sediment accumulation in front of low-flow channel. No accumulation in front the baffled section due to scour coming around bullnose. • Left bank sediment extended from edge of topography to front of hardened ramp low flow channel. • Some scour observed around right side of bullnose.
	MOD-6 Flushing Channel Open	• Sediment moved quickly down flushing channel, occasionally including the largest sized rocks in sediment blend. • Some scour around bullnose prevented sediment from accumulating upstream of the baffled section of the hardened ramp, but no scour hole formed on the right side. • Sediment mostly accumulated in front of low flow channel; apron was covered in sediment for all gates, including in front of flushing channel.
	MOD-6 Flushing Channel Removed	• Large, left-leaning bend in sediment deposition from end of left bank curving to diversion intake and low flow channel of ramp. • Scour around bullnose, which caused a low point of sediment deposition in front of the baffled portion of the hardened ramp (apron still visible).
Upstream of Diversion Intake	**MOD-6 Flushing Channel Closed**	• Sediment entirely filled in section in front of canal up to top of all canal gates. At points the sediment overtopped gates 2 and 3. • Flow over the gates increased amount of flow passing into canal even though setting remained consistent.
	MOD-6 Flushing Channel Open	• Sediment in front of canal built up in such a way to severely limit flow over gate 1, only gates 2-3 remained fully active. • Sediment extended uniformly from end of left bank to front of intake gates 1-3 of intake and then again until apron of hardened ramp.
	MOD-6 Flushing Channel Removed	• Sediment in front of canal up to top of all gates except for the potions closest to corners where scour would remove accumulating sediment. • Flow over the gates increased amount of flow passing into canal even though setting remained consistent, as seen in MOD-6 flushing channel closed.
Inside Diversion Intake	**MOD-6 Flushing Channel Closed**	• Behind intake gates 1-2 was filled with sediment up to top of gates. Gate 3 also had sediment immediately behind it, though not up as high. Gate 4 remained relatively clear of sediment behind gate due to scour around bend. • Rest of canal intake downstream of pier consistently filled in with sediment.

Location	Configuration	Observations
	MOD-6 Flushing Channel Open	• Intake gates 1-2 almost entirely overtopped. Sediment accumulated to such an elevation behind the pier that it became a sand bar with almost no flow overtopped. There was some scour behind intake gate 4. • Rest of canal intake downstream of pier consistently filled in with sediment.
	MOD-6 Flushing Channel Removed	• Large sand bar formed in middle of canal. Sediment accumulated to such an elevation that sand bar formed with almost no flow overtopping. • No sediment accumulated immediately behind gates except for around pier. Rest of canal intake downstream of pier, with the exception of the sand bar.
Downstream of Hardened Ramp	**MOD-6 Flushing Channel Closed**	• Downstream of low flow channel had some scour in triangular pattern. Scour almost as wide as low flow channel immediately after channel and widened out to end of model. • Last two rows of baffles almost completely filled in with sediment where flow transitioned to subcritical.
	MOD-6 Flushing Channel Open	• Scour hole from MOD-6 flushing channel closed remained downstream of low flow channel, however an additional scour hole formed downstream of flushing channel. • Scour patterns caused significant sediment to build up immediately downstream of baffled section of hardened ramp. • Slight transverse pattern seen in sediment deposition along last three rows of baffles.
	MOD-6 Flushing Channel Removed	• Lower quarter of hardened ramp baffle section entirely filled in with sediment. • Some scour forms after low flow channel, following left edge of rock topography, however it was less than previously seen.
Downstream of Dam	**MOD-6 Flushing Channel Closed**	• Sediment accumulated immediately downstream of the dam stilling basin and the hardened ramp. A ripple pattern was seen in the sediment deposition downstream of flushing channel and dam.
	MOD-6 Flushing Channel Open	• Sediment accumulated immediately downstream of the dam stilling basin and the hardened ramp. A ripple pattern was seen in the sediment deposition downstream of flushing channel and dam. • Sediment deposition was significantly higher on right side of hardened ramp with mostly scour to the left side.
	MOD-6 Flushing Channel Removed	• Sediment accumulated immediately downstream of the dam stilling basin and the hardened ramp. A ripple pattern was seen in the sediment deposition downstream of flushing channel and dam. • Sediment deposition was significantly higher on right side of hardened ramp with mostly scour to the left side.

Table B-14. Model observations for MOD-9 design with flushing channel closed, open, and removed at 6,000 ft^3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-9 Flushing Channel Closed**	• Left bank completely overtopped; channel location shifted closer to left bank. Right bank elevation 164 ft overtopped to about 576 ft upstream of the dam. • Right side of dam crest started to activate (bank has standing water), however left side still heavily favored.
	MOD-9 Flushing Channel Open	• Left bank entirely overtopped. Right bank elevation 164 ft exposed; partially submerged from about 576-768 ft upstream of the dam. • Right crest slightly active with standing water from approximately 118 ft upstream of the dam to the dam crest; still favoring left notch.
	MOD-9 Flushing Channel Removed	• Left bank entirely overtopped at elevation 164 ft and extended down to hardened ramp. Right bank elevation 164 ft partially submerged to about 384 ft upstream of the dam. • Dam crest fully utilized, more flow on left notch however right crest is active.
Upstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• Sand bar with sheet flow from end of left bank to the low flow section of the hardened ramp. • Scour around right side of bullnose; left side accumulated sediment near the baffled section of the hardened ramp where eddy drops sediment. • Hardened ramp has some sediment accumulating on upstream sill.
	MOD-9 Flushing Channel Open	• Some scour around the bullnose but no sediment deposition pattern on left side as seen in MOD-9 flushing closed. • Sediment at exit to low flow channel accumulated around the low flow section of the hardened ramp; apron and sill also covered in sediment on the baffled section of the hardened ramp from bullnose scour. • Edge around flushing channel wall caused some scour, thus no sediment deposition along left edge of low flow channel.
	MOD-9 Flushing Channel Removed	• Sediment in front of low flow channel; clear to apron in front of the baffled section of the hardened ramp. • Some scour around bullnose but not enough to fully expose rip rap.
Upstream of Diversion Intake	**MOD-9 Flushing Channel Closed**	• No longer can see large recirculation zone from 3,000 flushing closed MOD9, which prevented some sediment deposition in front of the canal. However. portion in front of intake gates 1-2 still remain at original topography with some minor deposition. • Majority of intake apron covered with thin layer of sediment and the scour hole under apron was still visible. • Some sediment on sill in front of intake gates 1-2.
	MOD-9 Flushing Channel Open	• No sediment on canal apron and sill in front of intake gates 3-4; partial sediment coverage on intake gates 1-2. • Sand bar has filled in majority of area in front of canal, however a small scour hole around apron remains. This created edge effect previously seen and documented in 3,000 and 6,000 ft^3/s MOD-9 trials.
	MOD-9 Flushing Channel Removed	• Sediment deposited up to canal apron, but not on sill, however sediment seems to be equal height as top of gates. This accumulation pattern is perpendicular to the new edge of canal and is at the same height as sediment that accumulated in front of the low flow channel. • Sill in front of intake gates 1-2 entirely clear of sediment deposition.
Inside Diversion Intake	**MOD-9 Flushing Channel Closed**	• Sediment accumulated behind all intake gates. • Scour sediment pattern seen behind intake gate 2 around pier. However, the rest of the canal is filled in with sediment.
	MOD-9 Flushing Channel Open	• Same scour pattern as previously seen in MOD-9 flushing closed behind canal pier. • Rest of canal filled in with sediment.

Location	Configuration	Observations
	MOD-9 Flushing Channel Removed	• Sediment deposition around intake gates 1, 3, 4. Scour hole behind intake gate 2 from approach flow angle (similar to other MOD-9 deposition patterns). • Rest of canal filled in with sediment..
Downstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• Sediment deposition on hardened ramp baffled section past MOD-9 extension and 5 additional rows were fully covered in sediment to the top of the baffles. Area was also in subcritical flow, with water on top minimally influenced by baffles. • Scour pattern downstream of low flow channel continued to end of model.
	MOD-9 Flushing Channel Open	• Large recirculating eddy from flushing channel causing large scour downstream. • Low flow channel scour pattern remains from MOD-9 flushing closed Two "triangles" of scour downstream of flushing channel and low flow channel remain fairly separated as previously seen at 3,000 ft^3/s.
	MOD-9 Flushing Channel Removed	• Downstream end of low flow channel has a slight scour hole developing; flow pattern depositing sediment along concentrated area as previously seen in MOD-6. • Sediment deposition on hardened ramp baffled section past MOD-9 extension and 5 additional rows were fully covered in sediment to the top of the baffle. Area was also in subcritical flow, with water on top minimally influenced by baffles.
Downstream of Dam	**MOD-9 Flushing Channel Closed**	• Sediment accumulated immediately downstream of the dam stilling basin and the hardened ramp. A ripple pattern was seen in sediment deposition patterns after end of low flow channel and dam.
	MOD-9 Flushing Channel Open	• Sediment accumulated immediately downstream of the dam stilling basin and the hardened ramp. A ripple pattern was seen in sediment deposition patterns after end of low flow channel and dam.
	MOD-9 Flushing Channel Removed	• Sediment deposited in semi-circular pattern downstream of stilling basin. This depositional pattern is not seen until 12,000ft^3/s at other configurations.

Table B-15. Model observations for MOD-6 design with flushing channel closed, open, and removed at 12,000 ft^3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-6 Flushing Channel Closed**	• Left bank entirely overtopped. Right bank started to overtop at elevation 168 ft. • Dam crest fully utilized.
	MOD-6 Flushing Channel Open	• Left bank entirely overtopped. Right bank started to overtop at elevation 168 ft. • Dam crest fully utilized.
	MOD-6 Flushing Channel Removed	• Left bank entirely overtopped. Right bank elevation 164 ft overtopped through about 768 ft upstream of the dam, partially submerged at about 384 ft upstream of the dam. • Dam crest fully utilized, though still visibly deeper on the left side.
Upstream of Hardened Ramp	**MOD-6 Flushing Channel Closed**	• Sediment deposited in front of low flow channel. Apron in front of the baffled section of the ramp covered in sediment (except for portion eroded by bullnose). • Bullnose partially submerged, scour on the right as flow splits and eddy came away from side.
	MOD-6 Flushing Channel Open	• Apron exposed in front of flushing channel; flow split around channel wall caused turbulence at entrance, which enabled the flow to draw significant quantities of sediment. Sediment pattern in front of hardened ramp almost exact same as MOD-6 flushing channel closed. Sediment deposited in front of the low flow channel of the hardened ramp. Apron in front of the baffled section of the hardened ramp covered in sediment (except for portion eroded by bullnose). • Bullnose no longer submerged. However, scour on the right as flow splits and eddy came away from side still present.
	MOD-6 Flushing Channel Removed	• Sediment pattern around hardened ramp similar to other MOD-6 configurations. Low flow channel of hardened ramp filled with sediment. Apron still visible around the baffled section of the hardened ramp. • Bullnose overtopped during occasional wave action, with scour around right side.
Upstream of Diversion Intake	**MOD-6 Flushing Channel Closed**	• Sediment highest in front of all gates of intake. This gradually slopes down into hardened ramp with lowest point in front of bullnose where scour occurred. • As intake was not active, sediment accumulated evenly in front of all gates up to almost level with top of gates.
	MOD-6 Flushing Channel Open	• Similar pattern observed as MOD-6 flushing closed where sediment highest in front of all gates of intake. This gradually slopes down into hardened ramp with lowest point in front of bullnose where scour occurred. • Similar pattern observed as MOD-6 flushing closed where sediment accumulated evenly in front of all gates up to almost level with top of gates. However, slightly more of intake gate 4 was exposed due to scour around flushing channel.
	MOD-6 Flushing Channel Removed	• Sediment pattern almost identical to other MOD-6 configurations with more sediment deposition in front of intake to low flow channel. Less sediment accumulated upstream of bullnose. • Similar pattern observed as other MOD-6 configurations where sediment accumulated evenly in front of all gates up to almost level with top of gates. However, slightly more of intake gate 4 was exposed due to scour around flushing channel.
Inside Diversion Intake	**MOD-6 Flushing Channel Closed**	• As intake was not active, inside of diversion filled in uniformly with sediment with some minor scour behind left side of pier as water recirculated out of diversion.

Location	Configuration	Observations
	MOD-6 Flushing Channel Open	• As observed in MOD-6 flushing channel closed, inside of diversion filled in uniformly with sediment with some minor scour behind left side of pier as water recirculated out of diversion.
	MOD-6 Flushing Channel Removed	• As previously observed, intake was filled with sediment. Some scour around intake gate 2 to center back of pier and intake gate 4 by hardened ramp corner.
Downstream of Hardened Ramp	**MOD-6 Flushing Channel Closed**	• Scour downstream of low flow channel at entrance. Some recirculation of flow moving up flushing channel. • Downstream 6 rows of baffles partially filled in with sediment, however flow passes over tops of baffles.
	MOD-6 Flushing Channel Open	• Downstream 6 rows of baffles partially filled in with sediment, however flow passes over tops of baffles. • Scour downstream of flushing channel combined with previously existing scour from low flow channel. • Sediment deposition forms as a dune where scour is low point, followed by two dunes moving laterally towards dam stilling basin.
	MOD-6 Flushing Channel Removed	• Almost half of the downstream baffles are entirely filled in with sediment with transverse deposition pattern. This portion of the hardened ramp was in subcritical flow. • Scour downstream of low flow channel as seen in other configurations is no longer as prevalent (still lower than other sections downstream but can still observe deposition as opposed to scour).
Downstream of Dam	**MOD-6 Flushing Channel Closed**	• Sediment buildup down of stilling basin to the left. • Ripple pattern still observed downstream of dam and hardened ramp, however a semi-circular deposition pattern formed downstream of stilling basin.
	MOD-6 Flushing Channel Open	• Semi-circular deposition pattern was less pronounced than during MOD-6 flushing channel closed. However, ripple pattern still observed along with large sediment deposition to the left. • Immediately next to hardened ramp wall is a line of scour next to the increased deposition on the left of the stilling basin.
	MOD-6 Flushing Channel Removed	• Semi-circular deposition pattern was less pronounced than during MOD-6 flushing channel closed. However, ripple pattern still observed along with large sediment deposition to the left. • Immediately next to hardened ramp wall is a line of scour next to the increased deposition on the left of the stilling basin.

Table B-16. Model observations for MOD-9 design with flushing channel closed, open, and removed at 12,000 ft^3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-9 Flushing Channel Closed**	• Left bank completely overtopped. Right bank elevation 164 ft fully overtopped with elevation 168 ft overtopped at about 960 ft upstream of the dam. • Dam crest fully utilized.
	MOD-9 Flushing Channel Open	• Left bank completely overtopped. Right bank elevation 164 ft fully overtopped with elevation 168 ft overtopped at about 960 ft upstream of the dam. • Dam crest fully utilized, though still appears to be favoring left notch.
	MOD-9 Flushing Channel Removed	• Left bank completely overtopped and shifting towards hardened topography (moving more left). Right bank elevation 164 ft completely overtopped with elevation 168 ft overtopped at about 960 ft upstream of the dam. • Dam crest fully utilized, however flow still favors left side.
Upstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• Hardened ramp gates 2-3 filled with sediment. The only portions of the ramp that did not accrue sediment was due to scour from around bullnose or flushing channel wall. • Scour around bullnose on both sides (preventing sediment accumulation on gate 4 of ramp). Bullnose also overtopped.
	MOD-9 Flushing Channel Open	• Same deposition pattern in hardened ramp as MOD-9 closed (above). Hardened ramp gates 2-3 have sediment deposition and gates 1 and 4 are clear due to scour from flushing wall and bullnose, respectively. • Bullnose causing scour on both sides. Overtopped by occasional wave action.
	MOD-9 Flushing Channel Removed	• Low flow channel and left side of baffled section of the hardened ramp has sediment deposition. The only portions of the ramp that did not accumulate sediment was due to scour from around bullnose. Less scour around canal and flushing channel wall than seen in previous MOD-9 configurations. • Scour around bullnose on both sides (preventing sediment accumulation on right side of the baffled section). Bullnose also overtopped.
Upstream of Diversion Intake	**MOD-9 Flushing Channel Closed**	• Previous scour hole in front of intake apron filled in and level with original left bank topography. • Sand bar seen in previous trials now extending from canal sill to left notch of dam, with exception of area around bullnose.
	MOD-9 Flushing Channel Open	• Almost exact same sediment patterns as MOD-9 flushing channel closed. Previous scour hole in front of intake apron filled in and level with original left bank topography. • Sand bar seen in previous trials now extending from canal sill to left notch of dam, with exception of area around bullnose. • Some sediment drawn into flushing channel.
	MOD-9 Flushing Channel Removed	• Sill filled with sediment in front of intake gates 1-3. Intake gate 4 partially exposed due to scour from corner of wall. • Sediment on sill level with sediment in front of hardened ramp up to bullnose.
Inside Diversion Intake	**MOD-9 Flushing Channel Closed**	• No major changes to scour pattern behind canal pier (compared to 6,000 ft^3/s MOD-9). No sediment deposition immediately behind gates or pier. • Downstream portion of canal accumulating sediment.

Location	Configuration	Observations
	MOD-9 Flushing Channel Open	• Sediment deposition pattern similar to MOD-9 Flushing channel closed. No major changes to scour pattern behind canal pier. No sediment deposition immediately behind gates or pier. • Downstream portion of canal accumulating sediment.
	MOD-9 Flushing Channel Removed	• Scour around pier behind intake gate 2 as recirculation occurs, with even sediment deposition elsewhere.
Downstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• Almost half of downstream hardened ramp baffles filled in with sediment in transverse pattern seen in MOD-6. • Scour pattern downstream of low flow channel different from previous configurations. The pattern is not a triangle so much as a line with a higher accumulation of sediment to the left (on the bank) and the right where it joins with the transverse pattern from the baffles.
	MOD-9 Flushing Channel Open	• Flushing channel open did not impact the sediment pattern seen above in flushing channel closed. Almost half of downstream hardened ramp baffles filled in with sediment in transverse pattern seen in MOD-6. • Scour pattern downstream of low flow baffle different from previous configurations. The pattern is not a triangle so much as a line with a higher accumulation of sediment to the left (on the bank) and the right where it joins with the transverse pattern from the baffles.
	MOD-9 Flushing Channel Removed	• Transverse sediment deposition pattern seen in previous MOD-9 configurations clearer. • Downstream of hardened ramp forming scour hole at entrance to low flow channel with more sediment accumulation to the left (on the bank) and the right where it joins with the transverse pattern from the baffles. • Lower portion of ramp in subcritical flow past the MOD-9 addition.
Downstream of Dam	**MOD-9 Flushing Channel Closed**	• Semi-circular deposition pattern was less pronounced than during MOD-6 flushing channel closed/open. Ripple pattern still observed along with significant sediment deposition to the left. • Immediately next to hardened ramp wall is a line of scour next to the increased deposition on the left of the stilling basin.
	MOD-9 Flushing Channel Open	• Sediment pattern similar to flushing channel closed.
	MOD-9 Flushing Channel Removed	• Semi-circular deposition pattern was less pronounced than during MOD-6 flushing channel closed/open. Ripple pattern still observed along with significant sediment deposition to the left. • Immediately next to hardened ramp wall is a line of scour next to the increased deposition on the left of the stilling basin.

Table B-17. Model observations for MOD-6 design with flushing channel closed, open, and removed at 30,000 ft3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-6 Flushing Channel Closed**	• All banks overtopped except for right bank elevation 168 ft from about 480-672 ft upstream of the dam. • Channel continued to shift left, with sediment from left bank pushed onto hardened topography and right bank extending further into original channel. • Dam crest fully utilized.
	MOD-6 Flushing Channel Open	• All banks overtopped except for right bank elevation 168 ft from about 480-672 ft upstream of the dam. • Channel continued to shift left, with sediment from left bank pushed onto hardened topography and right bank extending further into original channel. • Dam crest fully utilized with more flow still coming over left bank.
	MOD-6 Flushing Channel Removed	• Right bank elevation 168 ft overtopped and slowly eroding. • Channel continued to shift left, with sediment from left bank pushed onto hardened topography and right bank extending further into original channel. Similar pattern to other MOD-6 configurations. • Dam crest completely utilized, still favoring left side.
Upstream of Hardened Ramp	**MOD-6 Flushing Channel Closed**	• Sediment accumulated in front of canal to left side of bullnose. From right side of bullnose to left crest of dam, sediment scour occurs. Bullnose was also entirely overtopped. • Flushing channel wall overtopped, thus the flushing channel was partially active with flow. • Sediment in front of hardened ramp accumulated on the apron in front of all gates with some sediment in front of low flow channel.
	MOD-6 Flushing Channel Open	• Hardened ramp apron visible in front of bullnose. Little sediment accumulated in front of low flow channel. • Bullnose overtopped, scour from eddy off right side creating similar sediment pattern as seen in MOD-6 flushing closed. • Even with flushing channel open, some flow came over flushing channel wall.
	MOD-6 Flushing Channel Removed	• Closed off flushing channel that is still in model overtopped, allowing some flow to bypass hardened ramp at entrance. • Sediment accumulated in front of canal to left side of bullnose. From right side of bullnose to left crest of dam, sediment scour occurred. Bullnose was also entirely overtopped. • Sediment accumulated in front of the low flow channel and on apron of hardened ramp.
Upstream of Diversion Intake	**MOD-6 Flushing Channel Closed**	• Sediment accumulated in front of intake gates almost up to top of all gates. • Intake gates was the highest point of sediment accumulation with a steady downslope to the bullnose.
	MOD-6 Flushing Channel Open	• Sediment accumulated in front of intake gates almost up to top of all gates. • Intake gates was the highest point of sediment accumulation with a steady downslope to the bullnose. Similar overall pattern to MOD-6 flushing channel closed with less accumulation on apron.
	MOD-6 Flushing Channel Removed	• Wake around water surface elevation sensor causing inaccurate readings. • Intake gates 1-2 almost buried upstream of gates and intake gate 4 has scour hole around edge with hardened ramp. Intake gates was the highest point of sediment accumulation with a steady downslope to the bullnose. Similar overall pattern to MOD-6 flushing channel closed.

Location	Configuration	Observations
Inside Diversion Intake	**MOD-6 Flushing Channel Closed**	• Sediment completely filled in the inside of the intake in a fairly uniform pattern. • Sediment accumulation was limited immediately behind the gates and in front of downstream slide gate pier • Downstream slide gate pier was overtopped and gates were fully submerged.
	MOD-6 Flushing Channel Open	• Intake filled with sediment except for immediately behind the gates. Gate 4 remained clear upstream and downstream of gate due to flushing channel activity. • Downstream slide gate pier was overtopped and gates were fully submerged.
	MOD-6 Flushing Channel Removed	• Intake filled with sediment except for immediately behind the gates. Gate 4 remained clear upstream and downstream of gate due sharp edge with hardened ramp. • Downstream slide gate pier was overtopped and gates were fully submerged.
Downstream of Hardened Ramp	**MOD-6 Flushing Channel Closed**	• Downstream wall of hardened ramp partially overtopped by water from dam side. This resulted in sediment accumulating in a transverse pattern. • Scour hole downstream of low flow channel continued to deepen. The scour hole was the only area where sediment did not accumulate downstream. • Recirculating eddy downstream of low flow channel caused water to move into flushing channel.
	MOD-6 Flushing Channel Open	• Downstream wall of hardened ramp partially overtopped by water from dam side. This resulted in sediment accumulating in a transverse pattern. • Scour hole downstream of low flow channel extended to include downstream of flushing channel. Scour hole continued to deepen and follow the same pattern as MOD-6 flushing closed. The scour hole was the only area where sediment did not accumulate downstream.
	MOD-6 Flushing Channel Removed	• Significant recirculation downstream of low flow channel allowed flow into the previous flushing channel. • Transverse deposition pattern seen in the other MOD-6 configurations present and slightly more defined. • Less flow from still basin overtopped wall of hardened ramp, only the end of wall was submerged.
Downstream of Dam	**MOD-6 Flushing Channel Closed**	• Downstream of stilling basin was the largest site of sediment deposition and accumulation in a semi-circular pattern. • Scour along wall of hardened ramp was filled in by sediment. • Sediment pattern from stilling basin extended to downstream of hardened ramp.
	MOD-6 Flushing Channel Open	• Downstream of stilling basin was the largest site of sediment deposition and accumulation in a semi-circular pattern. • Scour along wall of hardened ramp was filled in by sediment. • Sediment pattern from stilling basin extended to downstream of hardened ramp.
	MOD-6 Flushing Channel Removed	• Downstream of stilling basin was the largest site of sediment deposition and accumulation in a semi-circular pattern. • Scour along hardened ramp wall on stilling basin side still visible.

Table B-18. Model observations for MOD-9 design with flushing channel closed, open, and removed at 30,000 ft^3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-9 Flushing Channel Closed**	• All banks overtopped except for right bank elevation 168 ft from about 576-768 ft upstream of the dam. • Dam crest fully utilized. • Channel continued to shift left, with sediment from left bank pushed onto hardened topography and right bank extending further into original channel.
	MOD-9 Flushing Channel Open	• All banks overtopped except for right bank elevation 168 ft from about 576-768 ft upstream of the dam. • Dam crest fully utilized. However, left crest significantly more turbulent with more sediment carried over than right side. • Channel continued to shift left, with sediment from left bank pushed onto hardened topography and right bank extending further into original channel.
	MOD-9 Flushing Channel Removed	• All banks overtopped except for right bank elevation 168 from about 576-768 ft upstream of the dam. • Dam crest fully utilized. • Channel continued to shift left, with sediment from left bank pushed onto hardened topography and right bank extending further into original channel.
Upstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• Flushing channel partially overtopped from the hardened ramp spillover. • Low flow channel sill has sediment deposition. Baffled section of the hardened ramp did not accumulate sediment from scour bullnose. • Bullnose completely overtopped.
	MOD-9 Flushing Channel Open	• Flushing channel side overtopped with transverse waves all the way to end where there was a hydraulic jump. • Bullnose overtopped with significant scour and ripple pattern coming around right edge to under left side of crest. • Most sediment passed down hardened ramp without accumulating except in front of low flow channel where waves from flushing channel and bullnose overlapped and allowed sediment to deposit.
	MOD-9 Flushing Channel Removed	• Hardened ramp overtopped into previous flushing channel. • Bullnose entirely overtopped with scour and recirculating eddy around right side. • Low flow channel sill has sediment deposition. Baffled section of the hardened ramp did not accumulate sediment from scour bullnose.
Upstream of Diversion Intake	**MOD-9 Flushing Channel Closed**	• Sediment partially overtopped intake gates 1-3, scour around flushing channel wall prevented accumulation in front of intake gate 4. • As seen in MOD-6 at the same flow rate, intake gates were the high point for sediment accumulation, with levels dropping until bullnose, where scour was observed.
	MOD-9 Flushing Channel Open	• Sediment in front of ramp and intake built up in front of intake and flushing channel as extension of left bank but lowered and scoured in front of bullnose to dam crest on left notch (same pattern as seen in MOD-6 and MOD-9). • Sediment in front of intake still on sill, however, build up on gates washed away after the flushing channel was opened (intake gates 1-3 had sediment on sill; none accumulated on gate 4).
	MOD-9 Flushing Channel Removed	• Sediment in front of ramp and intake built up in front of canal and flushing channel as extension of left bank but lowered and scoured in front of bullnose to dam crest on left notch (same pattern as seen in MOD-6 and MOD-9). • Sediment in front of intake sill in front of gates 1-3; none accumulated in front gate 4 due to scour around edge of wall into hardened ramp.

Location	Configuration	Observations
Inside Diversion Intake	**MOD-9 Flushing Channel Closed**	• Intake filled with sediment in a uniform pattern except behind pier a small scour hole remained. • Gates were submerged along with downstream slide gate pier.
	MOD-9 Flushing Channel Open	• Intake still has sediment deposit with fairly uniform deposition throughout inside. • Some scour observed around gate 2 of pier. • Gates were submerged along with downstream slide gate pier.
	MOD-9 Flushing Channel Removed	• Slight scour behind gates 1-2 of intake and around pier next to gate 2. • Intake still has sediment deposit with fairly uniform deposition throughout inside. • Gates were submerged along with downstream slide gate pier.
Downstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• End of hardened ramp wall overtopped by stilling basin. Lower half of ramp, after bend, is in subcritical flow. • Transverse sediment pattern as seen in MOD-6 at same flow rate still observed. All baffles of MOD-9 extension to ramp filled in with sediment and barely visible.
	MOD-9 Flushing Channel Open	• Hydraulic jump at downstream end of flushing channel with recirculating eddy causing scour. • Upstream of MOD-9 insert filled in with sediment in similar transverse pattern to MOD-9 flushing channel closed and fully submerged. • Wall of hardened ramp overtopped; sediment accumulated on basin side of hardened ramp wall.
	MOD-9 Flushing Channel Removed	• Downstream of low flow channel flow recirculated up previously existing flushing channel. Scour extends to end of model. • Transverse pattern still visible, though not as defined as previous configurations. Baffles of MOD-9 extension mostly covered with sediment. • Wall of hardened ramp overtopped; sediment accumulated on basin side of hardened ramp wall.
Downstream of Dam	**MOD-9 Flushing Channel Closed**	• Large sand bar has re-formed downstream of ramp by end of model to the right of scour caused by low flow channel exit. • Recirculation from low flow channel filled up lower portion of flushing channel with flow and sediment. This caused scour and waves downstream of hydraulic jump. • Semi-circular deposition pattern visible downstream of stilling basin with scour along wall filled in.
	MOD-9 Flushing Channel Open	• Sand bar from MOD-9 flushing channel closed washed out. • Semi-circular deposition pattern visible downstream of stilling basin with scour along wall filled in.
	MOD-9 Flushing Channel Removed	• Semi-circular deposition pattern visible downstream of stilling basin with sediment filling almost to the top of the hardened ramp wall.

Appendix B-2: Contour Elevation Difference Maps

Contour elevation difference maps were created by comparing the baseline bed elevation condition prior to the test run to the resulting bed elevation data after data runs were completed.

For the MOD-6 design with the flushing channel closed and open, issues were found in the baseline point cloud data. Therefore, the resulting bed elevation data were compared to the baseline flushing channel removed point cloud.

Some data sets could not be fully resolved by the software program during difference mapping (MOD-6 flushing channel open at 3,000, 6,000, 12,000 ft^3/s and MOD-9 flushing channel removed at 30,000 ft^3/s).

Elevations Table			
Number	Min Elev	Max Elev	Color
1	-28	-5	
2	-5	-4	
3	-4	-3	
4	-3	-2	
5	-2	-1	
6	-1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

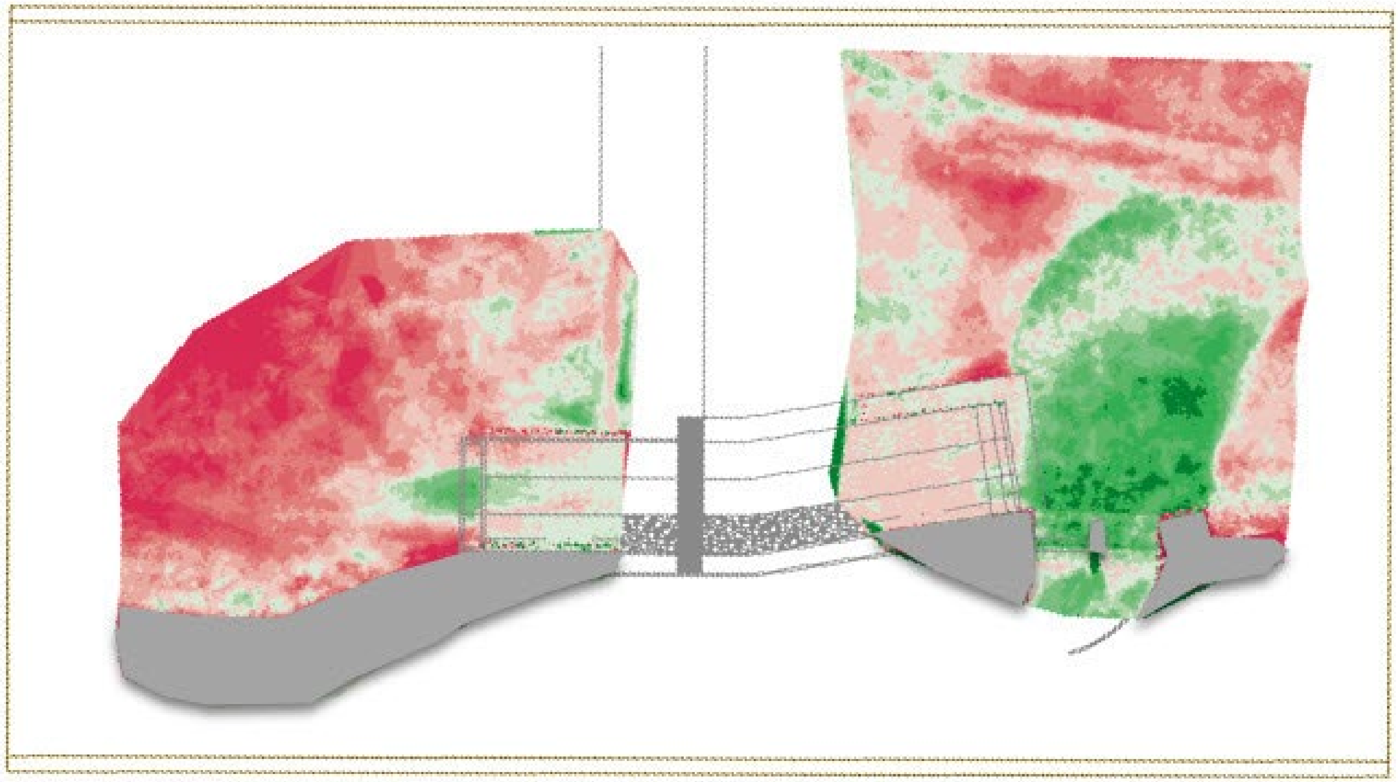


Figure B-125. Contour elevation difference map for MOD-6 design with flushing channel closed at 3,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel removed point cloud due to an absence of baseline data with the flushing channel installed. Flow is from right to left.

Elevations Table

Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

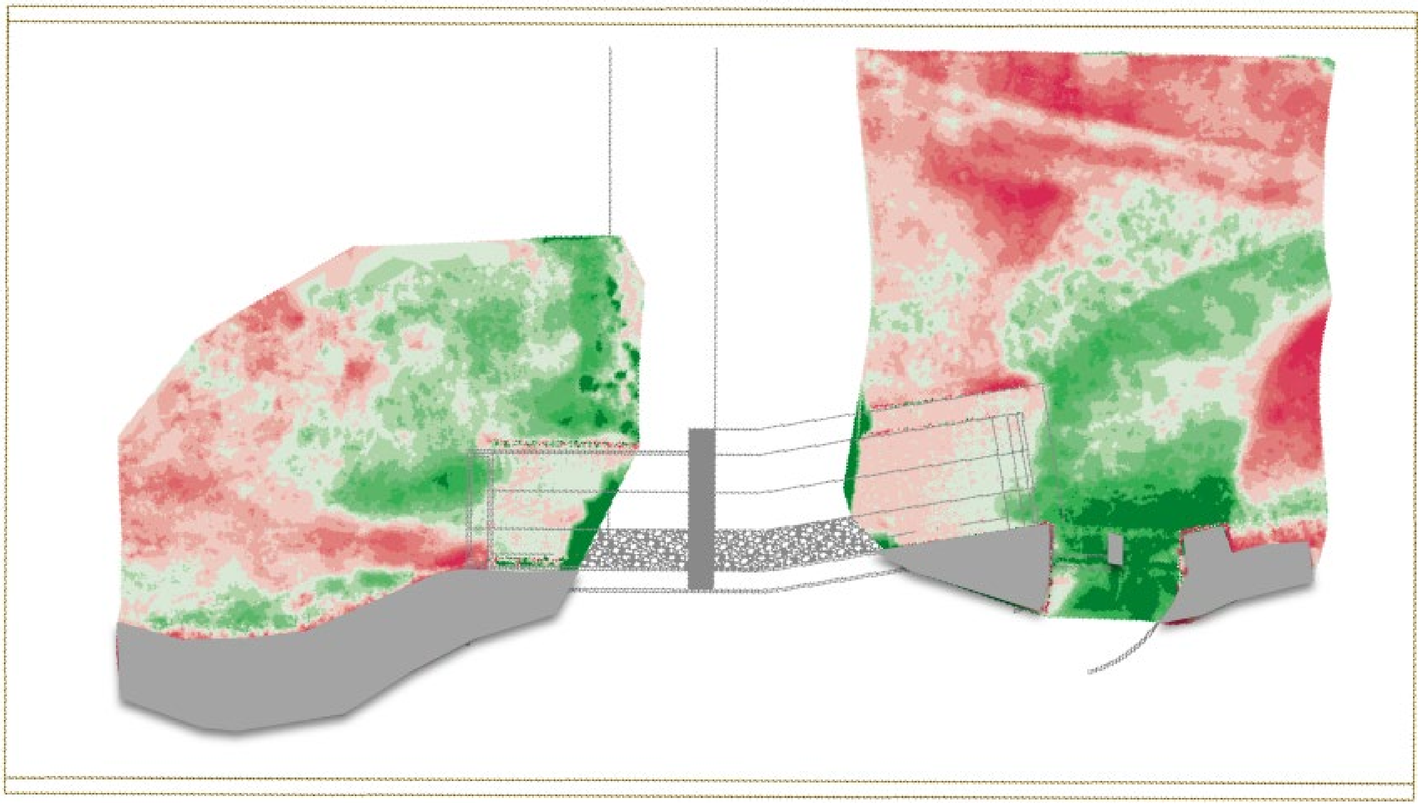


Figure B-126. Contour elevation difference map for MOD-6 design with flushing channel closed at 6,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel removed point cloud due to an absence of baseline data with the flushing channel installed. Flow is from right to left.

Elevations Table			
Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

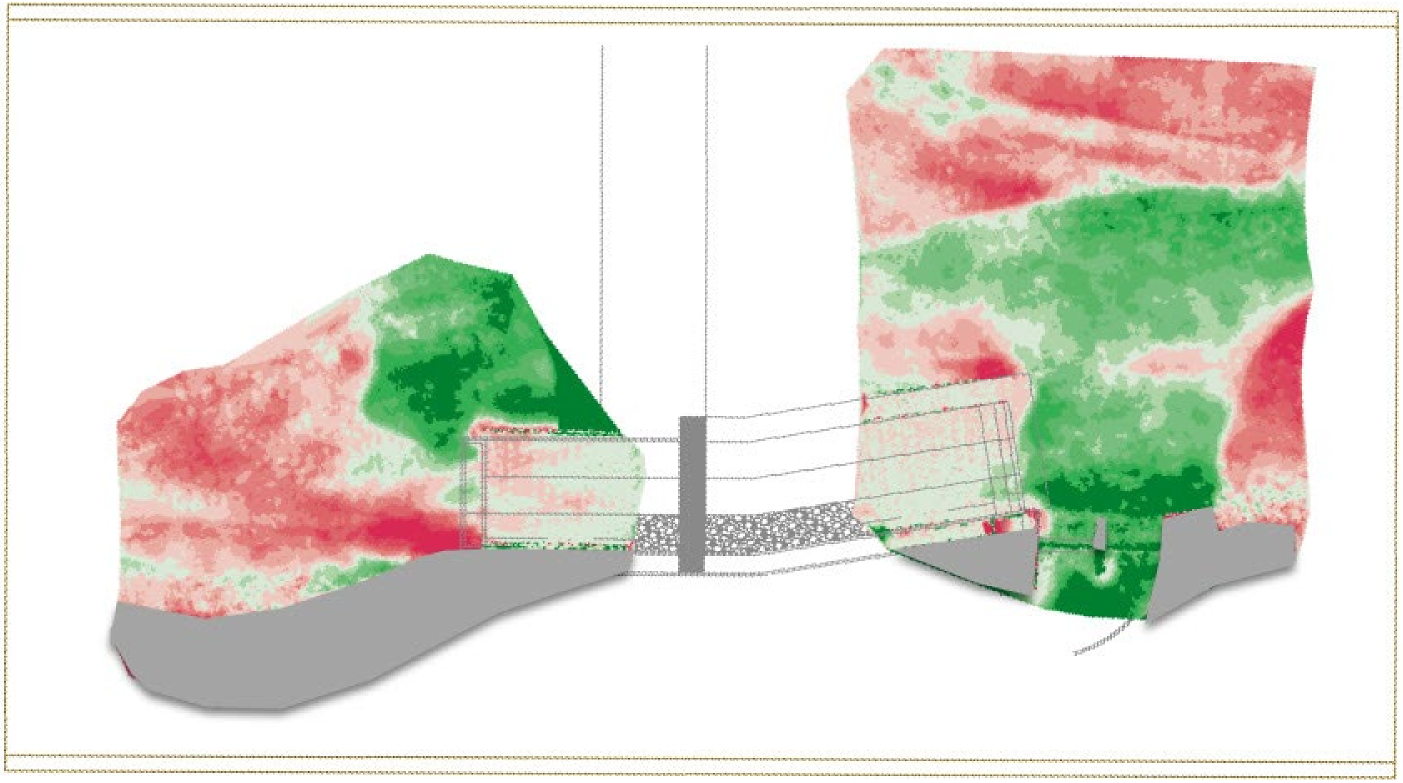


Figure B-127. Contour elevation difference map for MOD-6 design with flushing channel closed at 12,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel removed point cloud due to an absence of baseline data with the flushing channel installed. Flow is from right to left.

Elevations Table			
Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

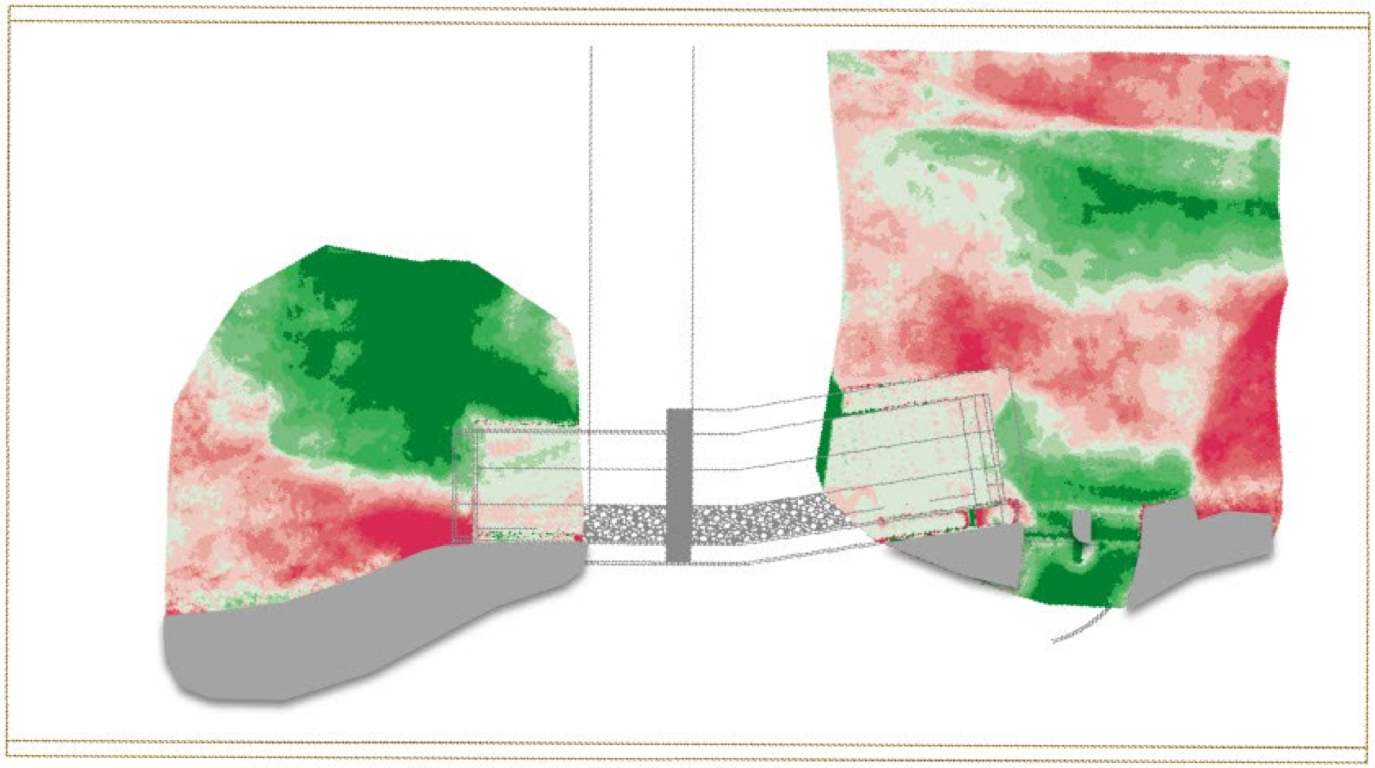


Figure B-128. Contour elevation difference map for MOD-6 design with flushing channel closed at 30,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel removed point cloud due to an absence of baseline data with the flushing channel installed. Flow is from right to left.

Elevations Table			
Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

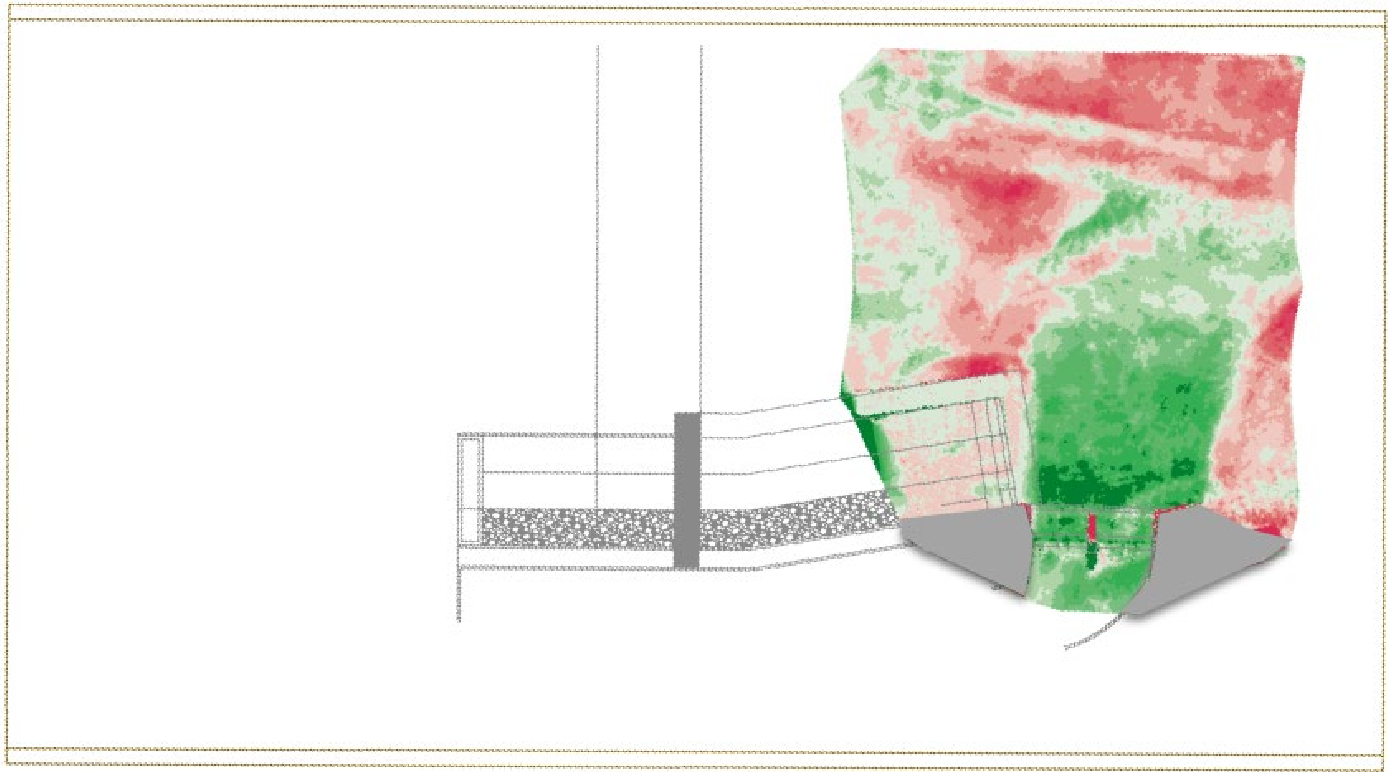


Figure B-129. Contour elevation difference map for MOD-6 design with flushing channel open at 3,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel removed point cloud due to an absence of baseline data with the flushing channel installed. Flow is from right to left.

Elevations Table			
Number	Min Elev	Max Elev	Color
1	-28	-5	
2	-5	-4	
3	-4	-3	
4	-3	-2	
5	-2	-1	
6	-1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

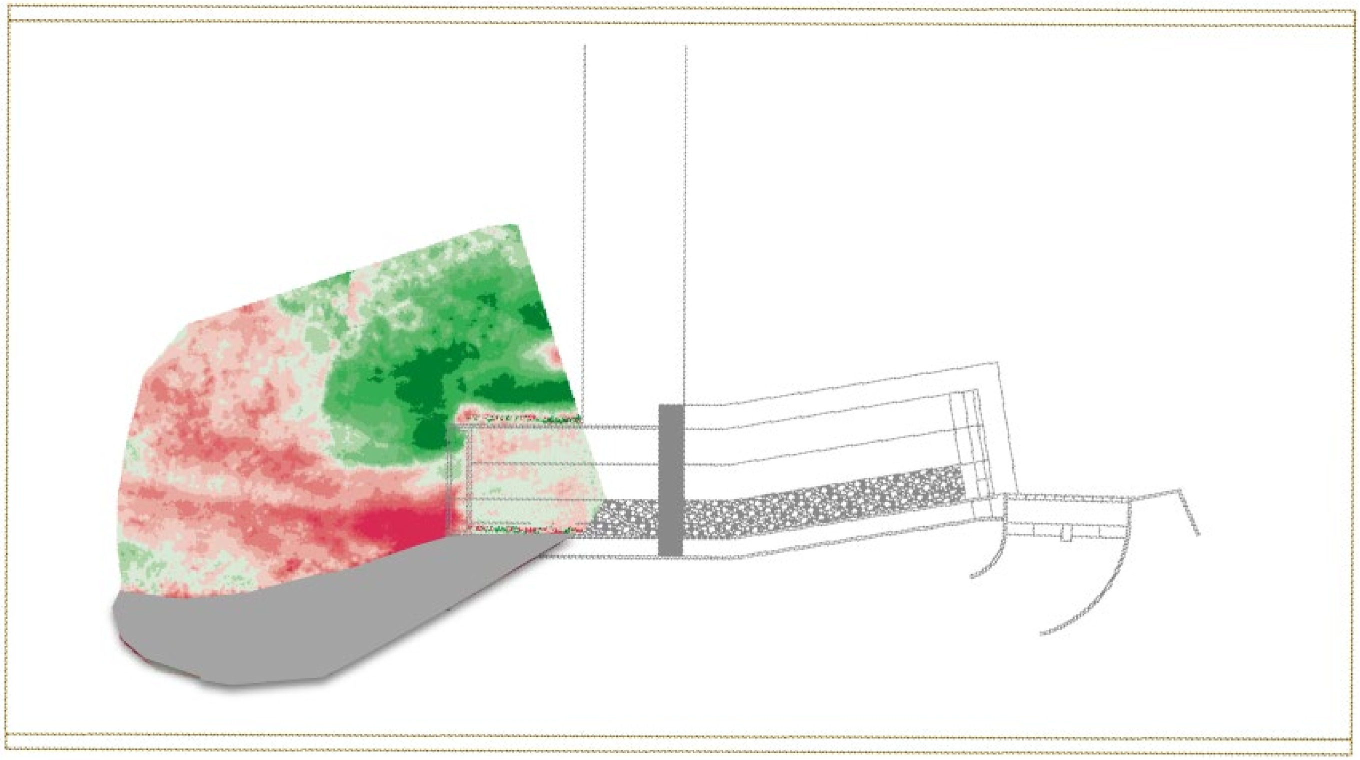


Figure B-130. Contour elevation difference map for MOD-6 design with flushing channel open at 12,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel removed point cloud due to an absence of baseline data with the flushing channel installed. Flow is from right to left.

Elevations Table			
Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

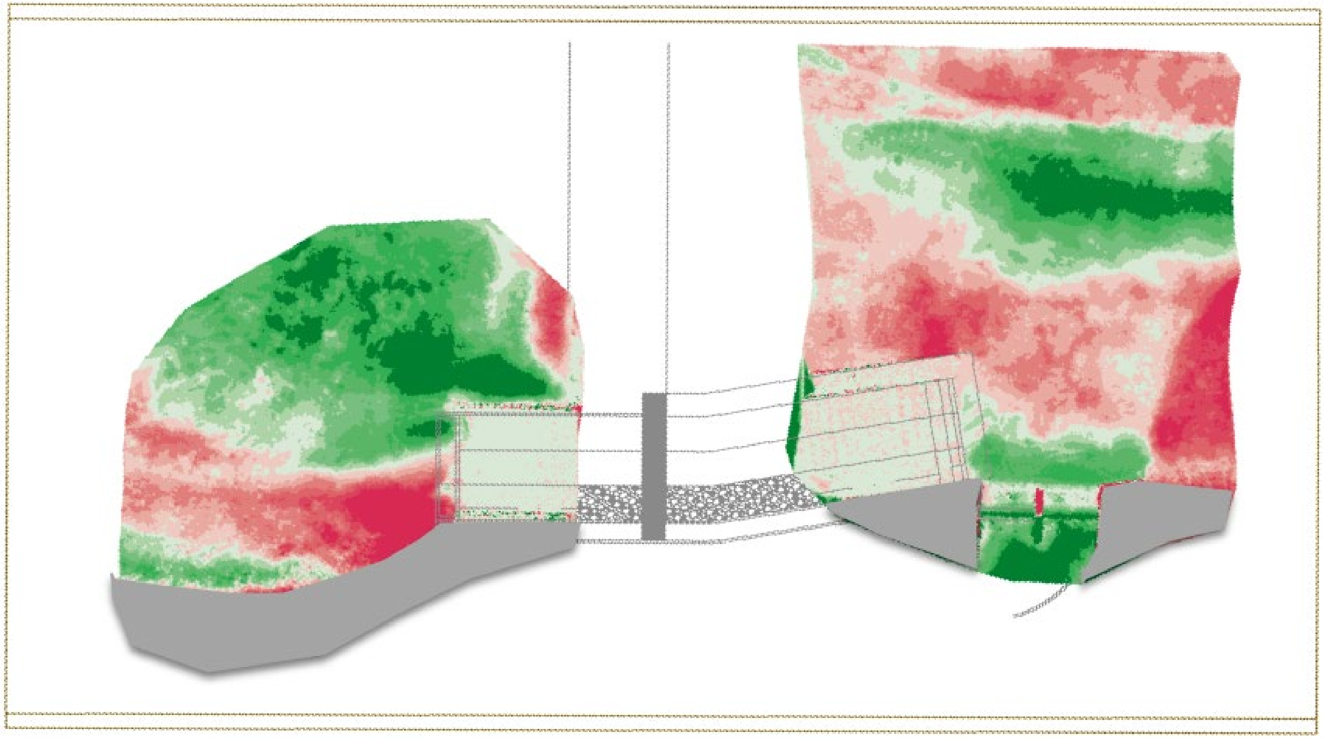


Figure B-131. Contour elevation difference map for MOD-6 design with flushing channel open at 30,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel removed point cloud due to an absence of baseline data with the flushing channel installed. Flow is from right to left.

Elevations Table			
Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

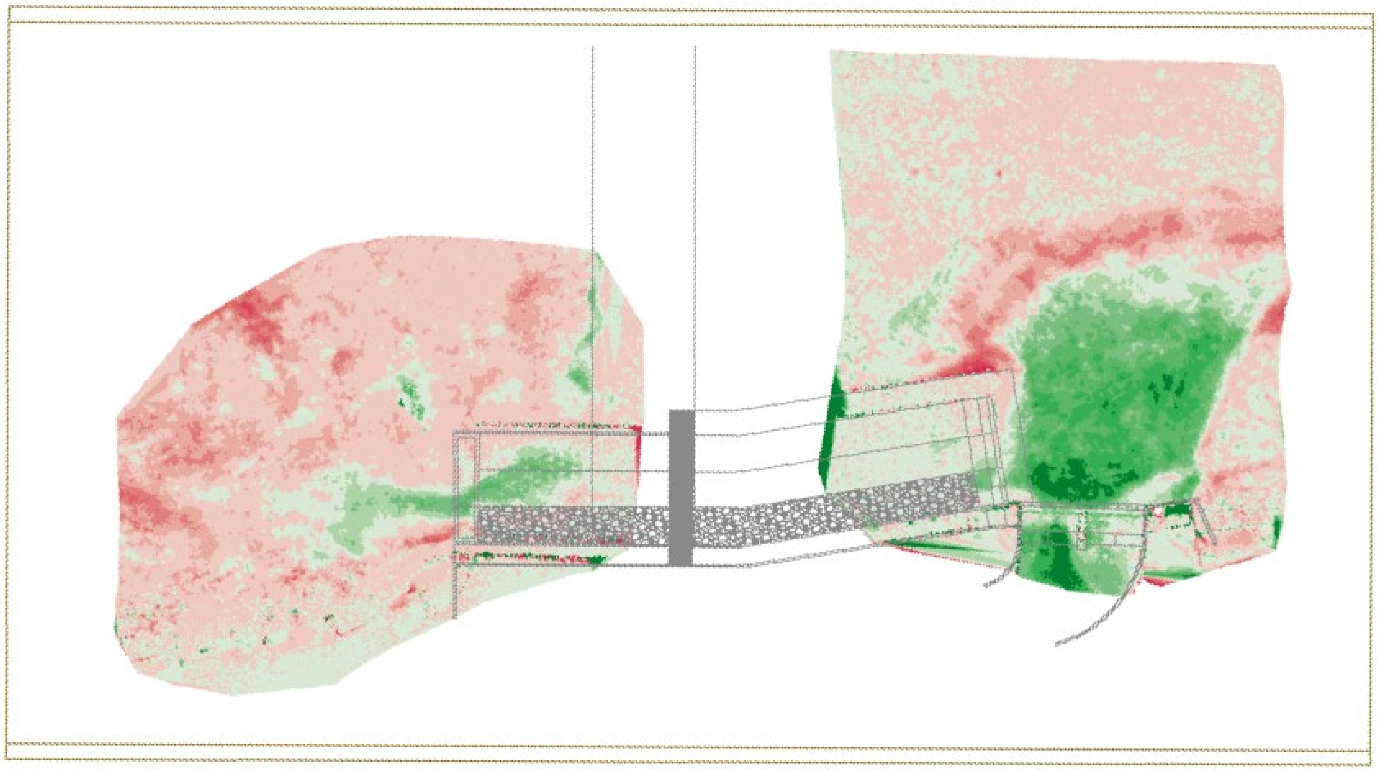


Figure B-132. Contour elevation difference map for MOD-6 design with flushing channel removed at 3,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel removed point cloud. Flow is from right to left.

Elevations Table			
Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

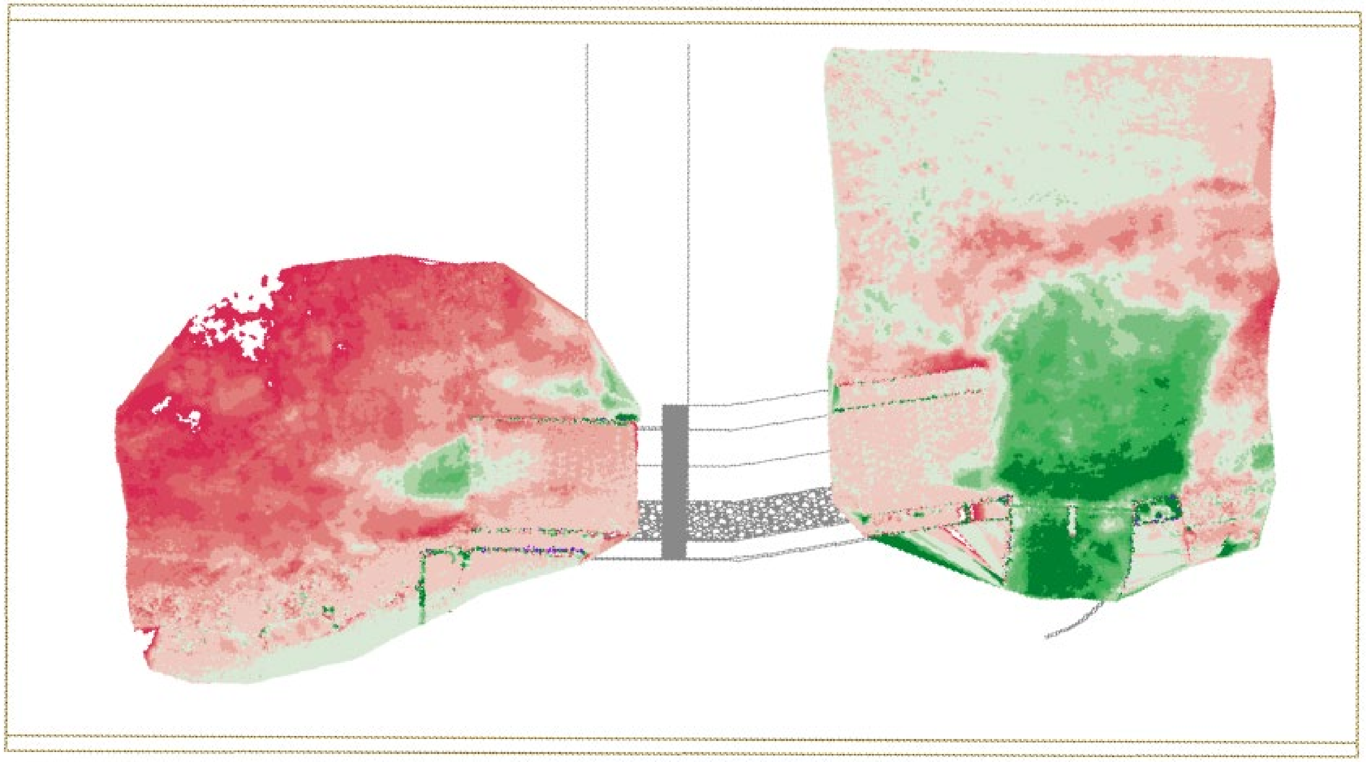


Figure B-133. Contour elevation difference map for MOD-6 design with flushing channel removed at 6,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel removed point cloud. Flow is from right to left.

Elevations Table			
Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

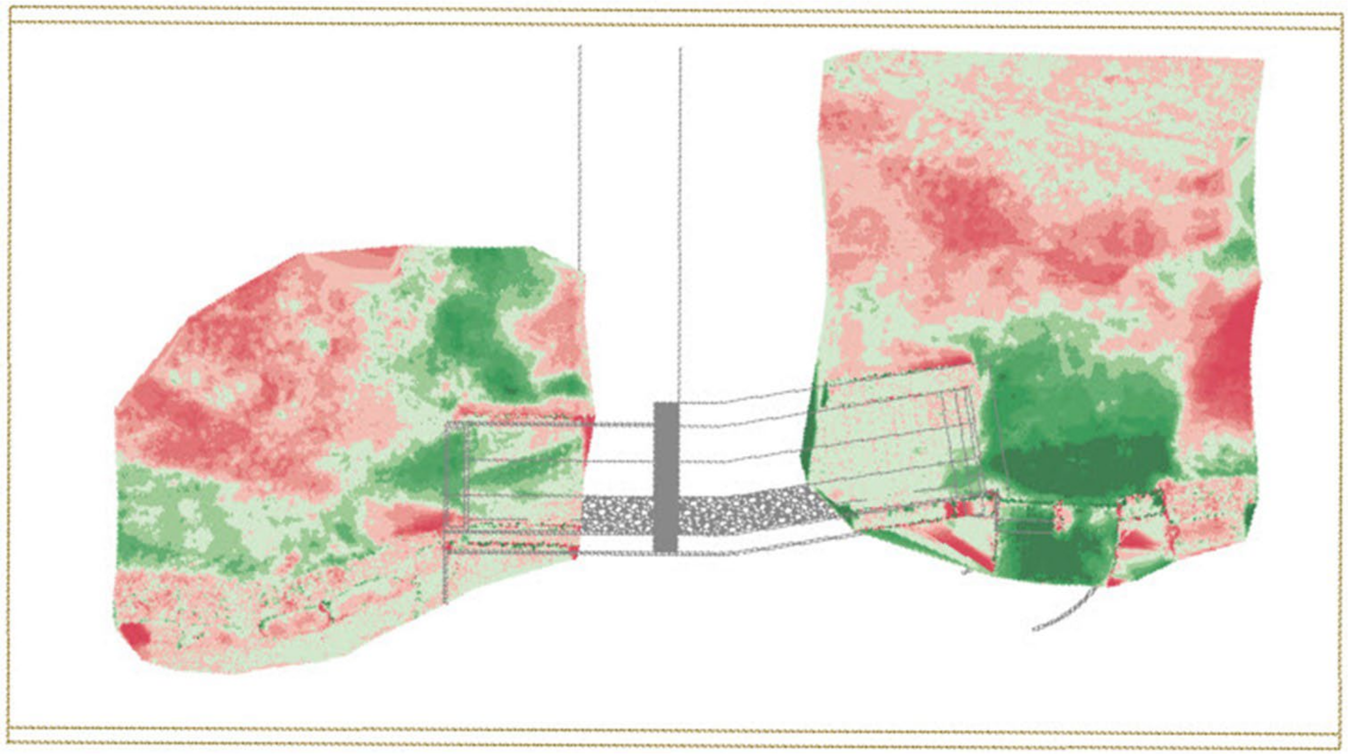


Figure B-134. Contour elevation difference map for MOD-6 design with flushing channel removed at 12,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel removed point cloud. Flow is from right to left.

Elevations Table

Number	Min Elev	Max Elev	Color
1	-28	-5	
2	-5	-4	
3	-4	-3	
4	-3	-2	
5	-2	-1	
6	-1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

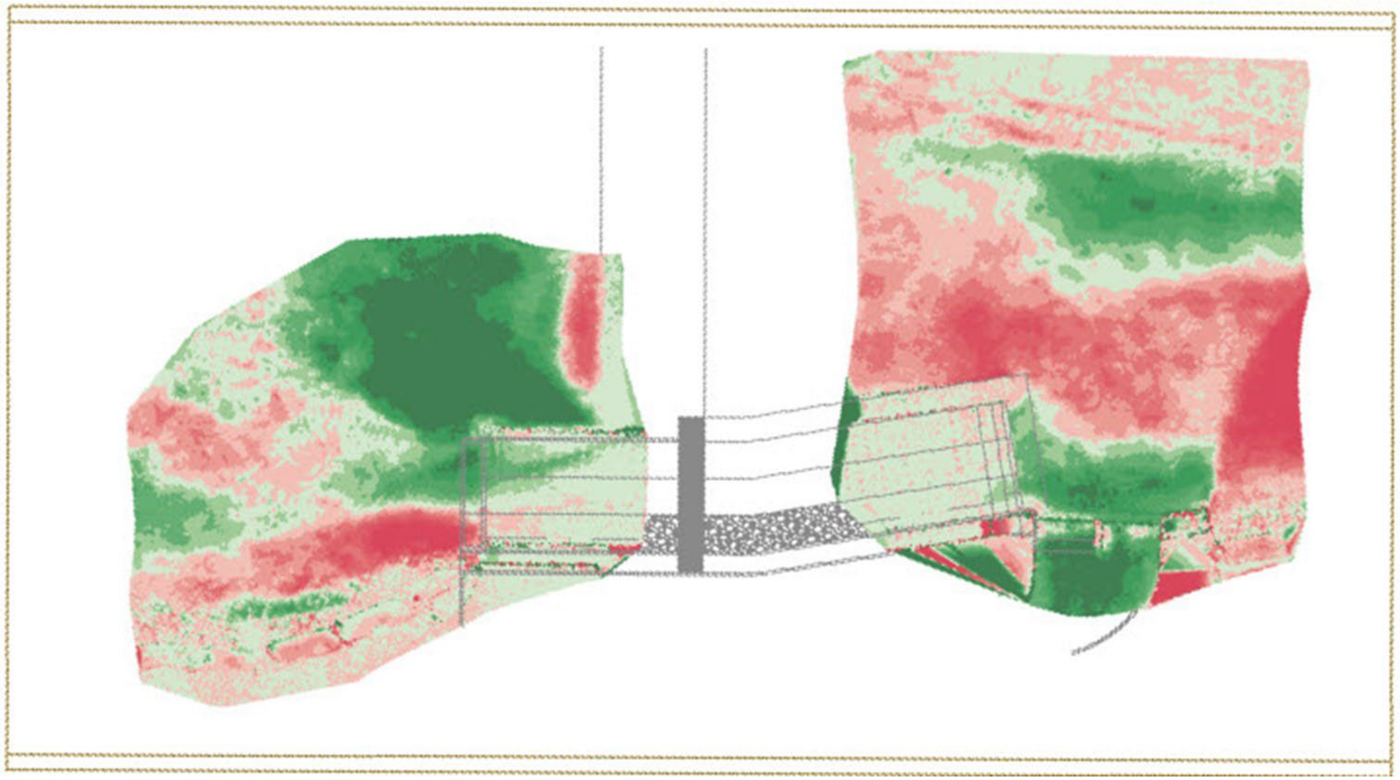


Figure B-135. Contour elevation difference map for MOD-6 design with flushing channel removed at 30,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel removed point cloud. Flow is from right to left.

Elevations Table

Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

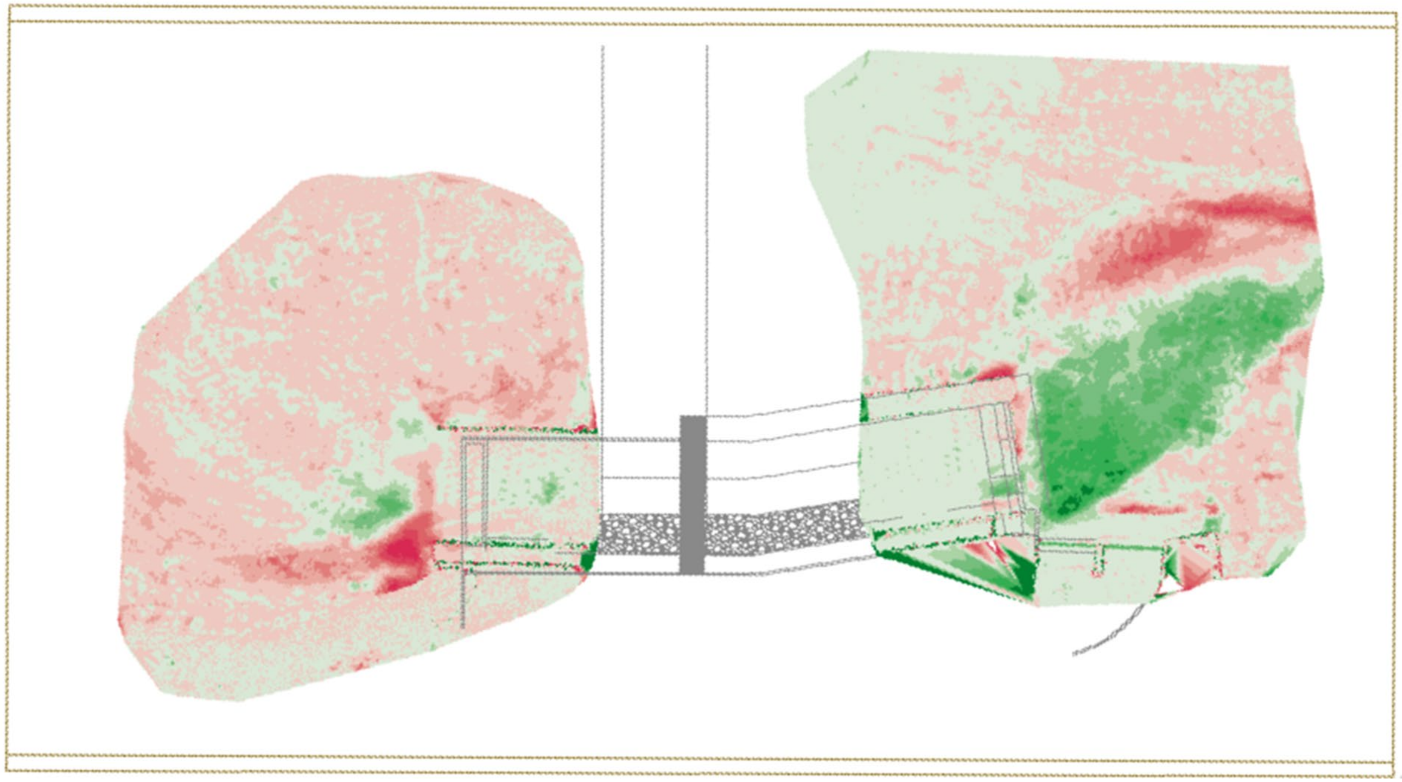


Figure B-136. Contour elevation difference map for MOD-9 design with flushing channel closed at 3,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel closed point cloud. Flow is from right to left.

Elevations Table

Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

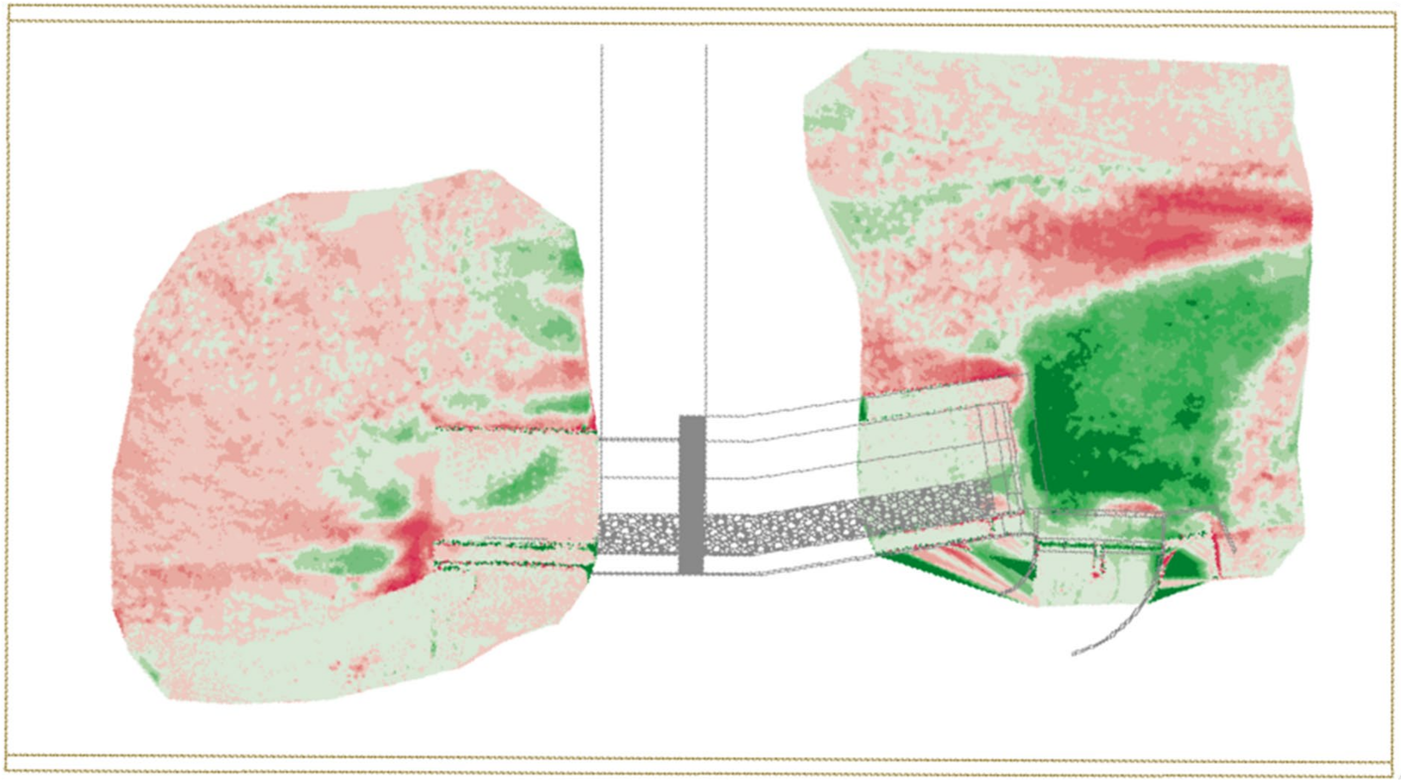


Figure B-137. Contour elevation difference map for MOD-9 design with flushing channel closed at 6,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel closed point cloud. Flow is from right to left.

Elevations Table

Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

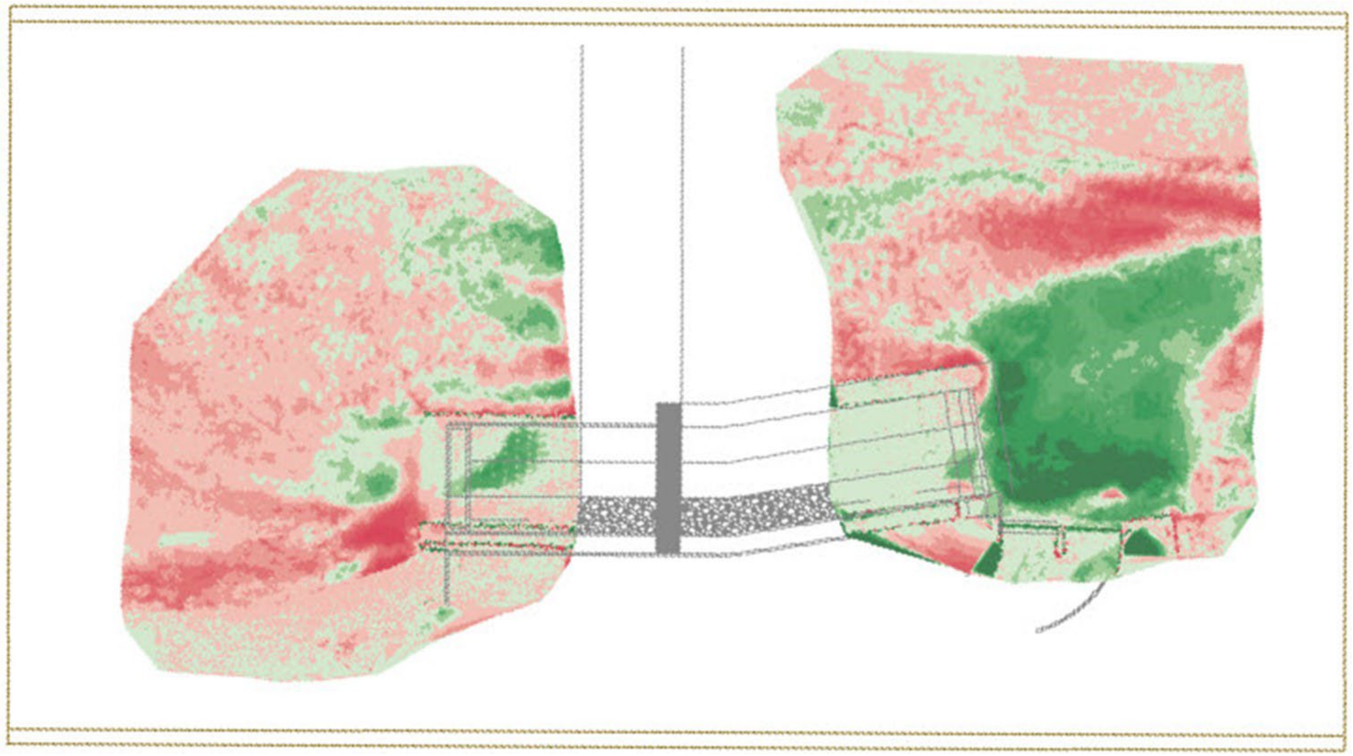


Figure B-138. Contour elevation difference map for MOD-9 design with flushing channel closed at 12,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel closed point cloud. Flow is from right to left.

Elevations Table

Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

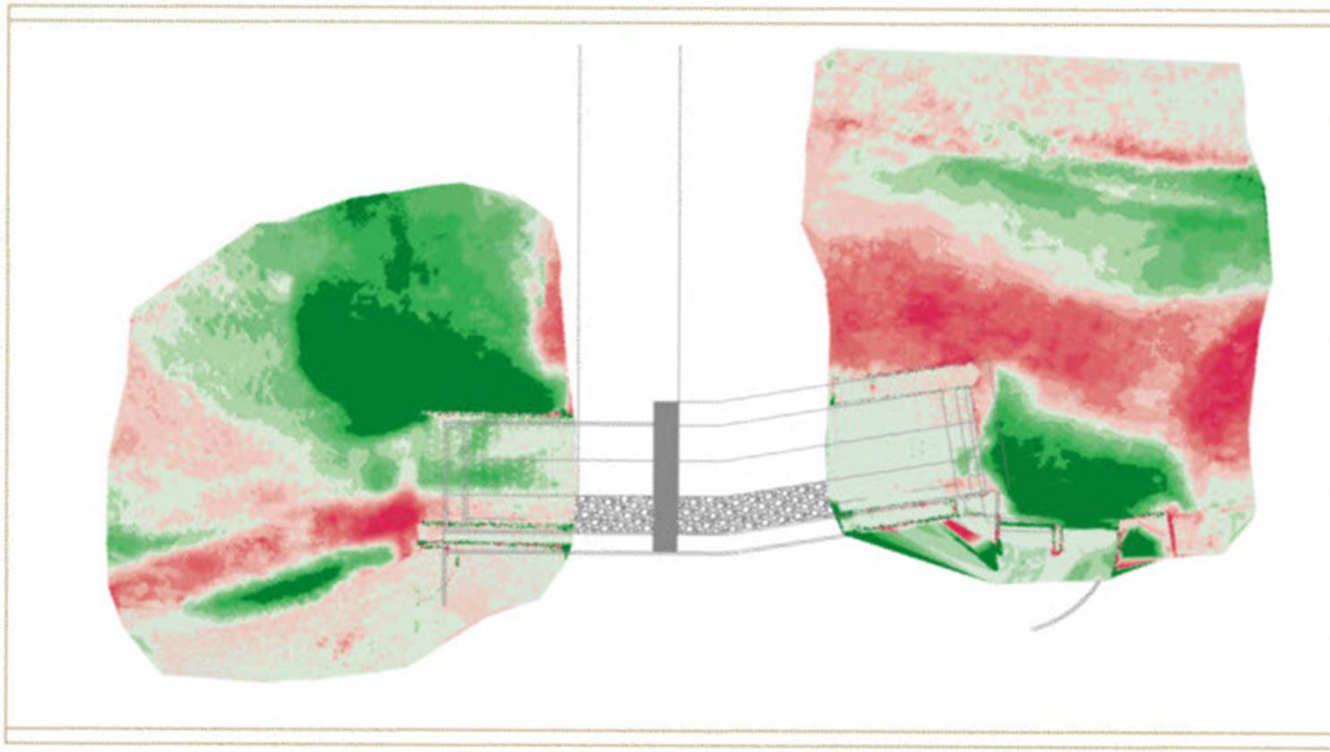


Figure B-139. Contour elevation difference map for MOD-9 design with flushing channel closed at 30,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel closed point cloud. Flow is from right to left.

Elevations Table			
Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

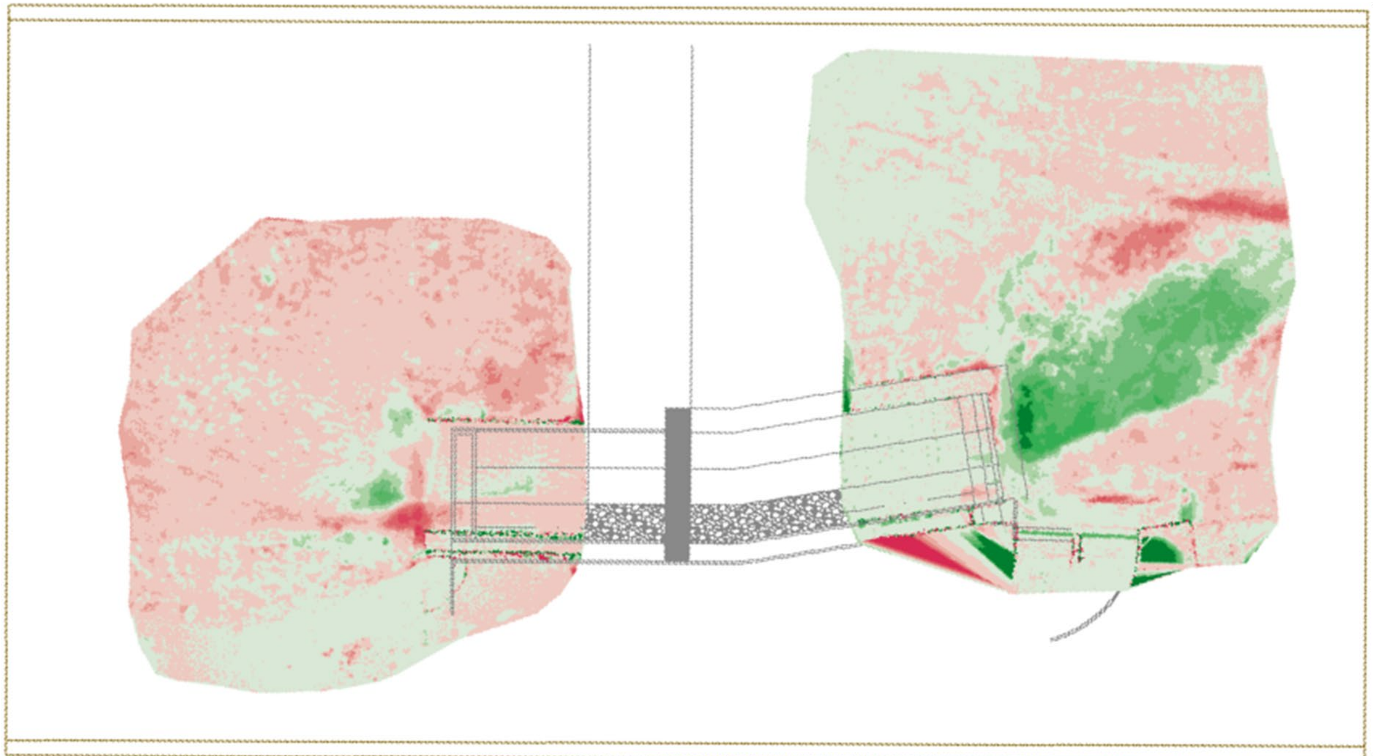


Figure B-140. Contour elevation difference map for MOD-9 design with flushing channel open at 3,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel open point cloud. Flow is from right to left.

Elevations Table			
Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

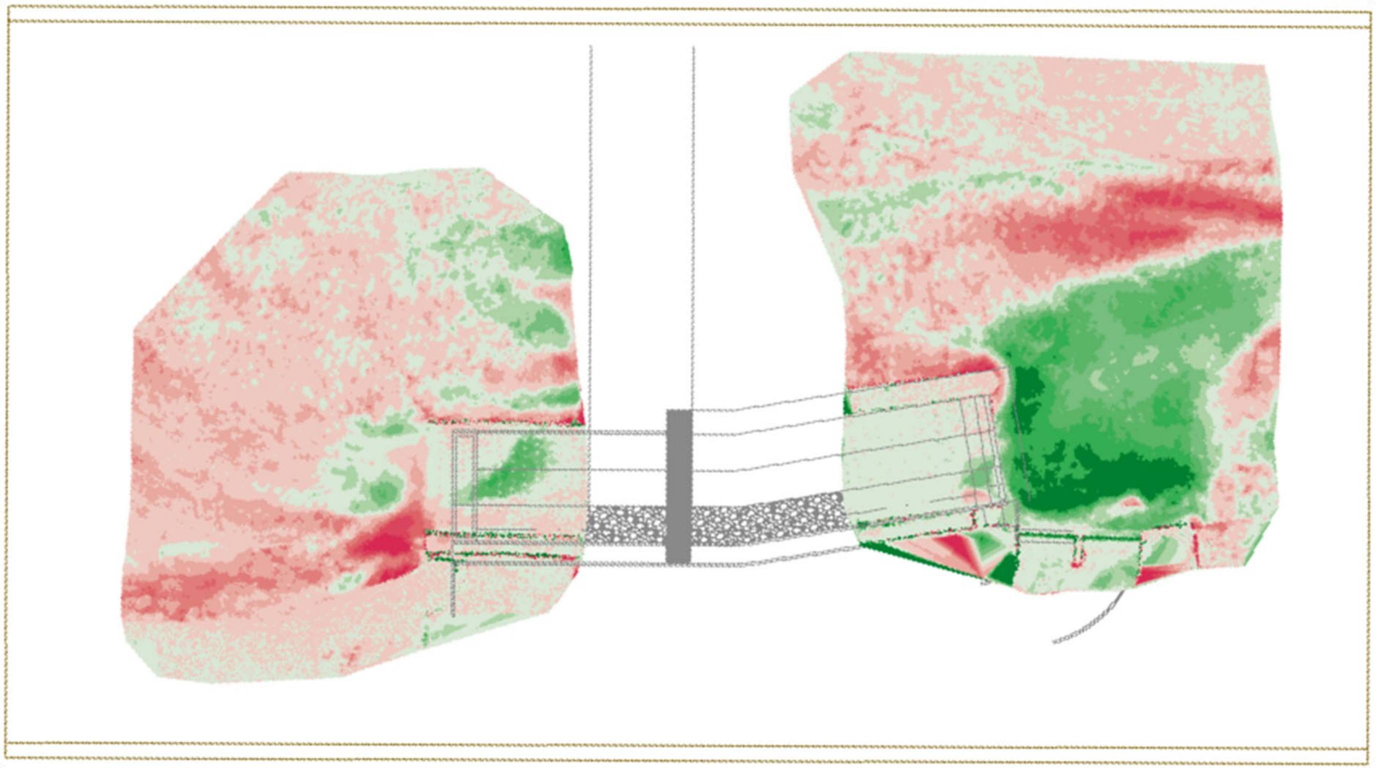


Figure B-141. Contour elevation difference map for MOD-9 design with flushing channel open at 6,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel open point cloud. Flow is from right to left.

Elevations Table			
Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

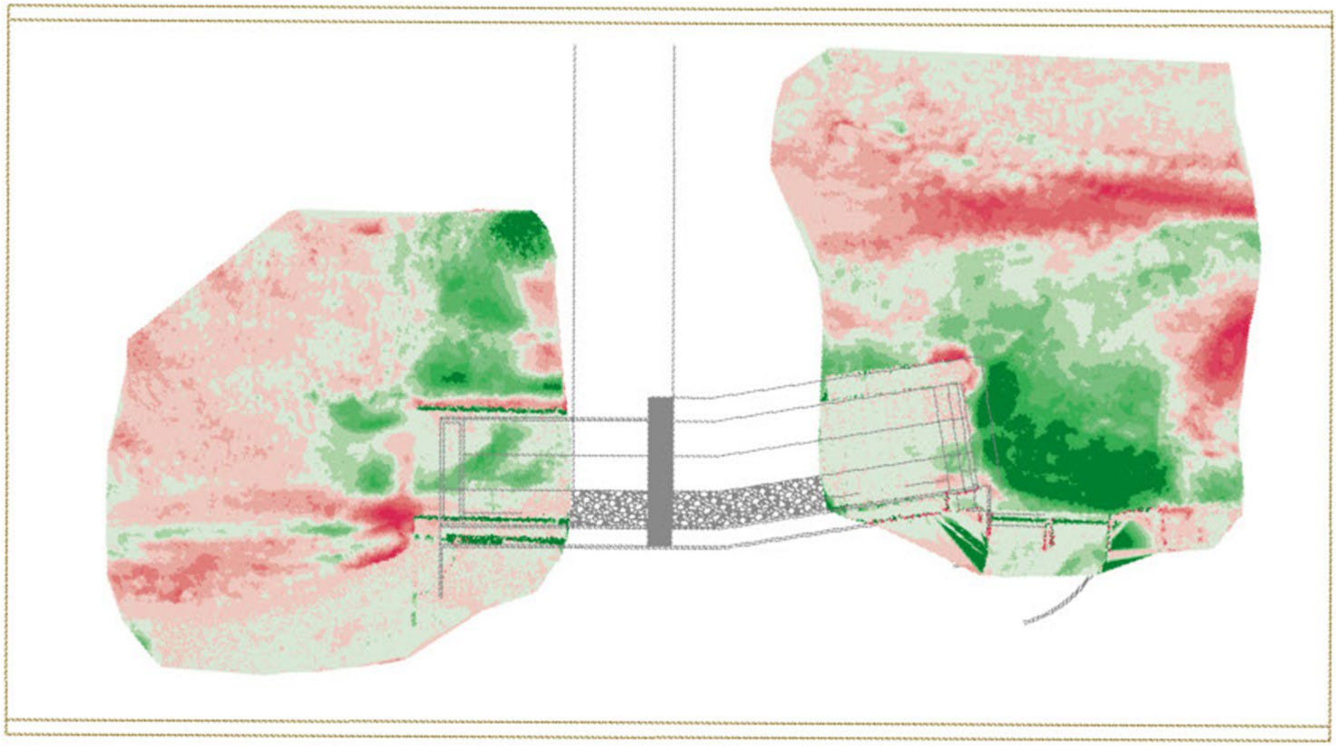


Figure B-142. Contour elevation difference map for MOD-9 design with flushing channel open at 12,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel open point cloud. Flow is from right to left.

Elevations Table			
Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

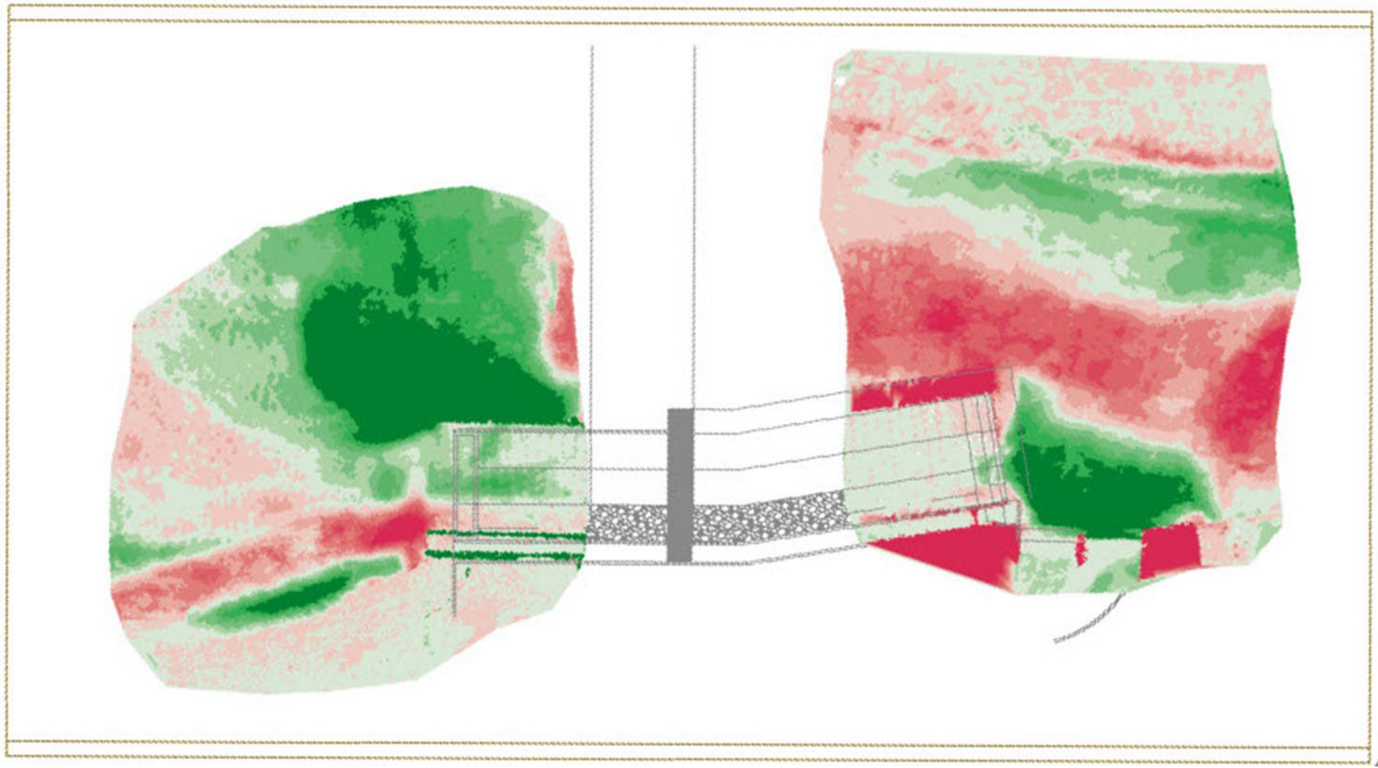


Figure B-143. Contour elevation difference map for MOD-9 design with flushing channel open at 30,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel open point cloud. Flow is from right to left.

Elevations Table

Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

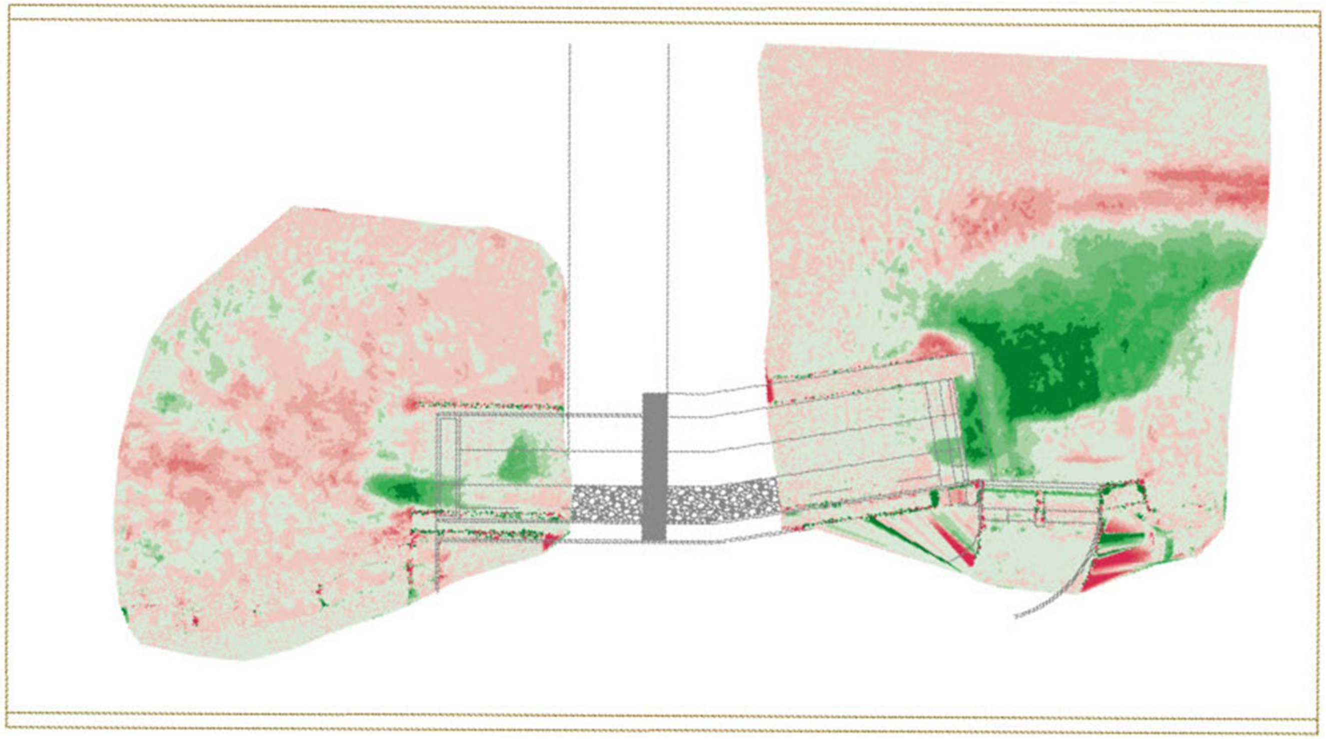


Figure B-144. Contour elevation difference map for MOD-9 design with flushing channel removed at 3,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel removed point cloud. Flow is from right to left.

Elevations Table			
Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

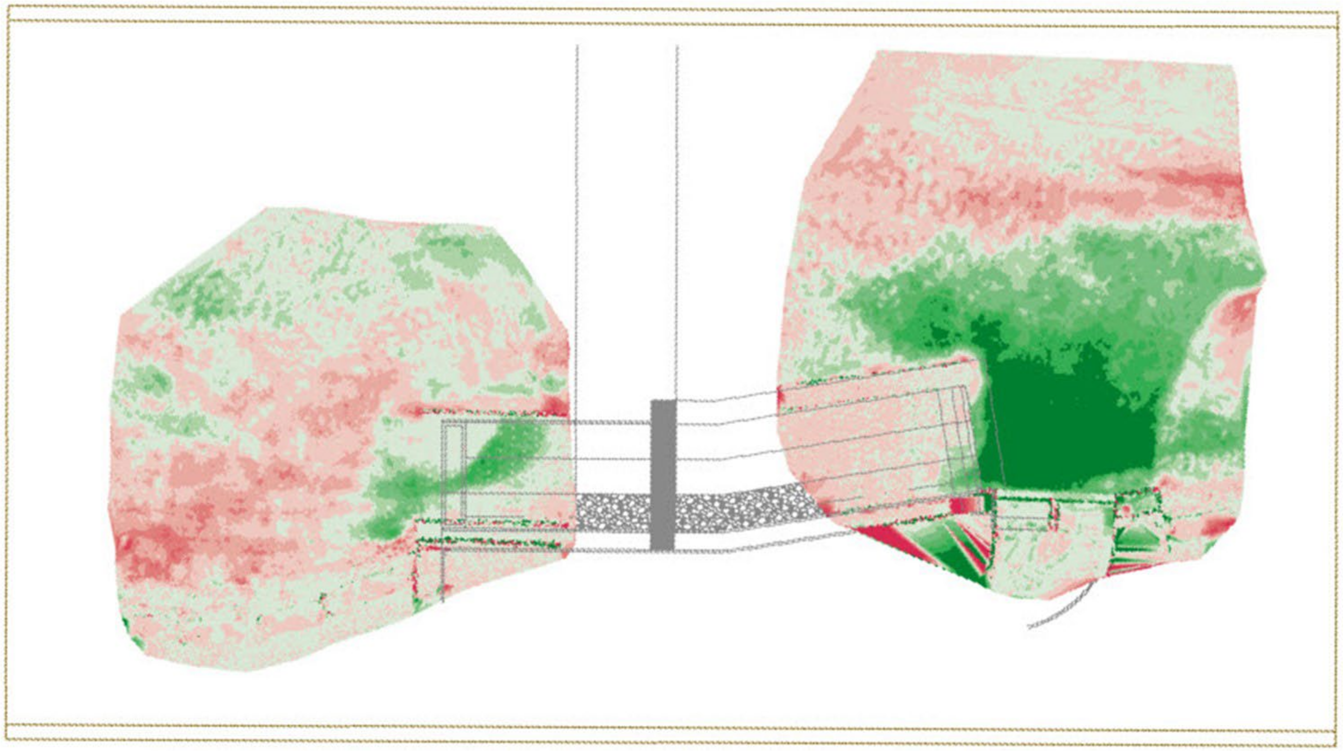


Figure B-145. Contour elevation difference map for MOD-9 design with flushing channel removed at 6,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel removed point cloud. Flow is from right to left.

Elevations Table			
Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

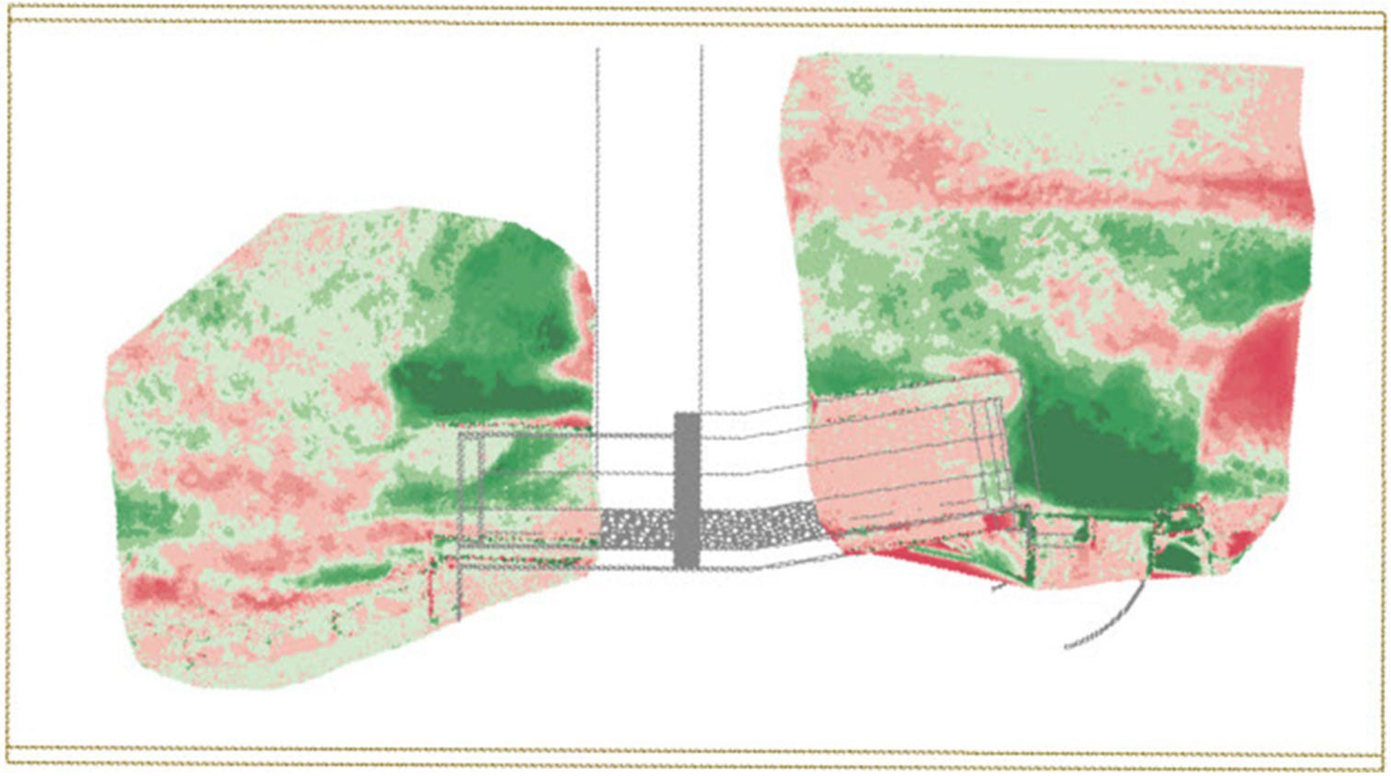


Figure B-146. Contour elevation difference map for MOD-9 design with flushing channel removed at 12,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel removed point cloud. Flow is from right to left.

Elevations Table

Number	Min Elev	Max Elev	Color
1	−28	−5	
2	−5	−4	
3	−4	−3	
4	−3	−2	
5	−2	−1	
6	−1	0	
7	0	1	
8	1	2	
9	2	3	
10	3	4	
11	4	5	
12	5	29	

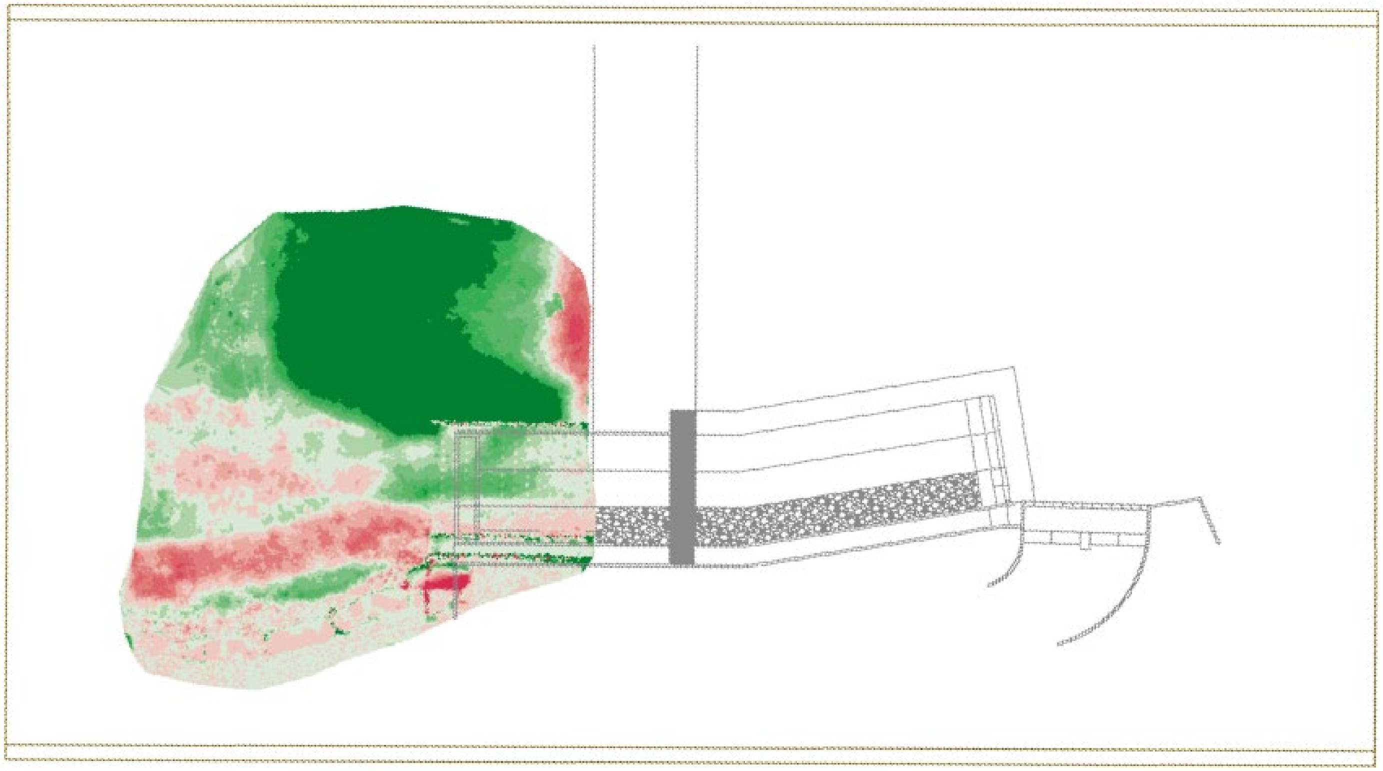


Figure B-147. Contour elevation difference map for MOD-9 design with flushing channel removed at 30,000 ft^3/s river flow. The resulting bed elevation data after the test run was compared to the baseline flushing channel removed point cloud. Flow is from right to left.

Appendix C: Summary of 1:12 Scale Baseline Results

Test Results and Observations for MOD-6 and MOD-9 Design Configurations

For the 1:12 model, the flushing channel open and closed configurations were tested at four flow rates: 6,000 ft^3/s, 3,000 ft^3/s, 1,500 ft^3/s, and 270 ft^3/s. At the beginning of each test series the model was run at 6,000 ft^3/s for at least 6 hours to set the initial upstream bathymetry and sediment features. This bathymetry was considered the initial condition for comparison in each of the bedform difference contour maps. The flushing channel removed configuration was not tested in this model due to findings from the 1:24 baseline testing.

For each of the tested flow rates, general model observations are summarized. Contour elevation plots and photographs are included to compare bed topography for MOD-6 and MOD-9 designs. Color maps of LSPIV-derived prototype surface velocity magnitudes in the key area upstream of diversion entrance and hardened ramp for the MOD-6 and MOD-9 designs are displayed.

Table B-19. Average water surface elevations for each flow condition tested for the MOD-6 configuration.

River Flow Rate (ft^3/s)	Upstream Intake (ft)	Downstream Intake (ft)	Dam Crest (ft)	Tailwater (ft)
270 (flushing closed)	157.15	153.88	160.50	143.04
270 (flushing open)	157.95	153.56	160.22	142.70
1,500 (flushing closed)	159.08	158.32	160.53	142.68
1,500 (flushing open)	159.27	157.60	160.32	143.49
3,000 (flushing closed)	161.06	157.72	161.39	144.05
3,000 (flushing open)	161.13	159.71	161.34	145.13
6,000 (flushing closed)	162.48	161.80	162.50	146.17
6,000 (flushing open)	162.36	162.20	162.41	146.42

Table B-20. Average water surface elevations for each flow condition tested for the MOD-9 configuration.

River Flow Rate (ft^3/s)	Upstream Intake (ft)	Downstream Intake (ft)	Dam Crest (ft)	Tailwater (ft)
270 (flushing closed)	158.84	157.01	160.69	140.10
270 (flushing open)	158.41	155.03	160.67	143.06
1,500 (flushing closed)	160.74	159.55	161.14	145.01
1,500 (flushing open)	160.95	160.28	161.19	143.62
3,000 (flushing closed)	162.76	161.89	162.85	144.19
3,000 (flushing open)	162.41	162.70	162.65	144.14
6,000 (flushing closed)	163.74	162.66	163.63	145.66
6,000 (flushing open)	163.41	163.67	163.53	146.42

Table B-21. Flow split data between the canal diversion, dam overflow, and hardened ramp for the MOD-6 configuration. For the 1:12 model, 6,000 ft^3/s (4,900 ft^3/s into box extents).

River Flow Rate (ft^3/s)	Canal Diversion Flow Rate (ft^3/s)	Dam Flow Rate (ft^3/s)	Hardened Ramp Flow Rate (ft^3/s)
270 (flushing closed)	54	0	216
270 (flushing open)	0	0	270
1,500 (flushing closed)	660	0	840
1,500 (flushing open)	0	0	1500
3,000 (flushing closed)	830	320	1850
3,000 (flushing open)	0	300	2700
6,000 (flushing closed)	826	1269	2805
6,000 (flushing open)	0	1150	3750

Table B-22. Flow split data between the canal diversion, dam overflow, and hardened ramp for the MOD-9 configuration. For the 1:12 model, 6,000 ft^3/s (4,900 ft^3/s into box extents).

River Flow Rate (ft^3/s)	Canal Diversion Flow Rate (ft^3/s)	Dam Flow Rate (ft^3/s)	Hardened Ramp Flow Rate (ft^3/s)
270 (flushing closed)	108	0	162
270 (flushing open)	0	0	270
1,500 (flushing closed)	839	0	726
1,500 (flushing open)	0	0	1500
3,000 (flushing closed)	835	852	1442
3,000 (flushing open)	0	660	2390
6,000 (flushing closed)	826	1799	2225
6,000 (flushing open)	0	1660	3140

River Flow 6,000 ft^3/s

MOD-6 Flushing Channel Closed

At 6,000 ft^3/s, the upstream portion of the model was submerged. Fine and coarse sediment moved from the upstream channel and deposited on the upstream end of the hardened ramp in front of the low flow channel and on the diversion sill onto the canal intake gates. The flow diversion remained constant at approximately 825 ft^3/s throughout the test.

MOD-6 Flushing Channel Open

After the flushing channel was opened, some sediment in front of intake gates 3 and 4 and the low flow section of the hardened ramp was cleared. The left portion of the intake maintained previous sediment levels.

Downstream of the hardened ramp, sediment deposition remained unchanged from the flushing channel closed configuration. Scour was observed downstream of the flushing channel to the extent of the model.

MOD-9 Flushing Channel Closed

At 6,000 ft^3/s, the upstream portion of the model was submerged. The apron and gates of the hardened ramp remained relatively clear of sediment, even though the river deposited sediment immediately upstream of the low flow section of the hardened ramp in the bed form typically observed. As fine and coarse sediment approached the low flow section of the hardened ramp, it would be transported downstream without depositing on the hardened ramp.

Sediment deposition on the downstream portion of the hardened ramp happened in a semi-transverse pattern in the lower third of the baffled section. However, none of the baffles were inundated by the sediment and still had resting area available behind the baffles. Additionally, the left end of the baffled area has a large recirculation area. Scour was concentrated immediately downstream of the hardened ramp in line with the low flow channel.

MOD-9 Flushing Channel Open

After the flushing channel was opened, the apron in front of intake gates 3-4 was cleared of sediment. The sand bar in front of the hardened ramp shifted left, with sediment deposition mostly upstream of the hardened ramp. Additionally, most sediment passed down hardened ramp and flushing channel without accumulating except in front of low flow section of the hardened ramp where waves from flushing channel and ramp gates overlapped and allowed sediment to drop on apron in front of gates 1-2.

On the downstream portion of the hardened ramp, the sediment deposition pattern did not change from the flushing channel closed configuration, with a semi-transverse deposition pattern along the lower third of the ramp. The left end of the baffled area has a large recirculation area. Scour was concentrated immediately downstream of the low flow section of the hardened ramp and the flushing channel.

Figure C-1. View looking downstream after dewatering for MOD-6 design with flushing channel closed at 6,000 ft^3/s.

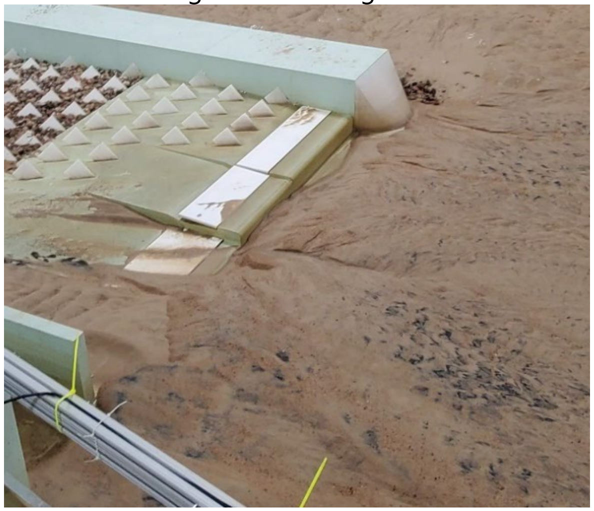


Figure C-2. View of ramp exit looking from left bank for MOD-6 design with flushing channel closed after 6,000 ft^3/s flow rate.

Figure C-3. View looking downstream after dewatering for MOD-9 design with flushing channel closed at 6,000 ft^3/s.

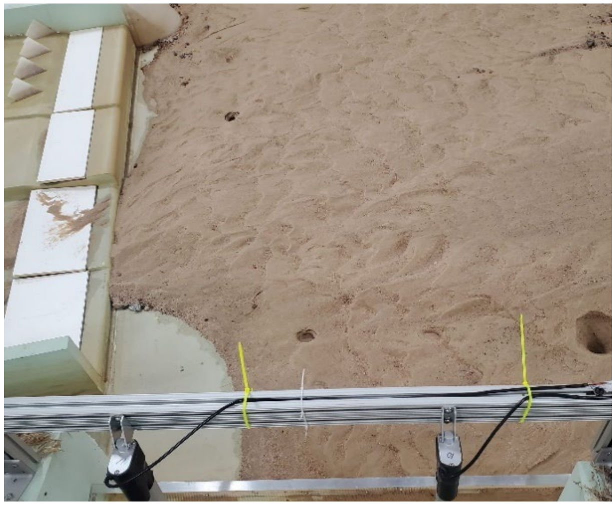


Figure C-4. View of ramp exit looking from left bank for MOD-9 design with flushing channel closed after 6,000 ft^3/s flow rate.

Figure C-5. View looking downstream after dewatering for MOD-6 design with flushing channel open at 6,000 ft^3/s.

Figure C-6. View of ramp exit looking from left bank for MOD-6 design with flushing channel open after 6,000 ft^3/s flow rate.

Figure C-7. View looking downstream after dewatering for MOD-9 design with flushing channel open at 6,000 ft^3/s.

Figure C-8. View of ramp exit looking from left bank for MOD-9 design with flushing channel open after 6,000 ft^3/s flow rate.

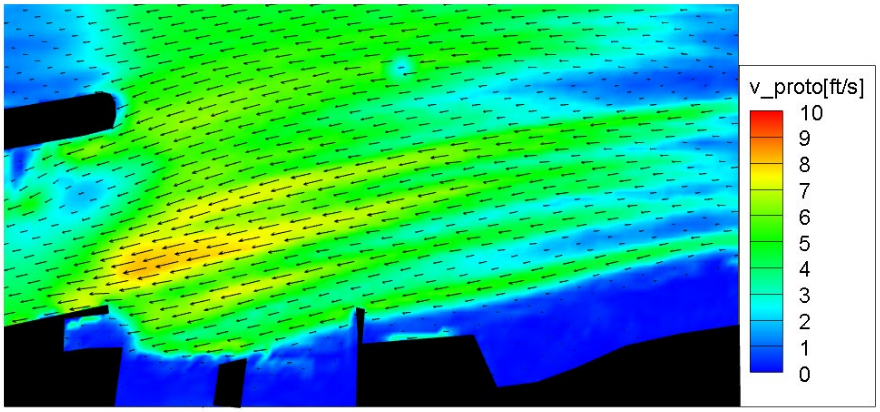


Figure C-9. Prototype velocity color map of surface velocities in area upstream of diversion entrance (bottom left) and hardened ramp (left) for MOD-6 design with flushing channel closed at 6,000 ft^3/s river flow.

Figure C-10. Views looking upstream from diversion canal of area upstream of diversion intake (bottom) and hardened ramp (left) for MOD-6 design with flushing channel closed at 6,000 ft^3/s river flow.

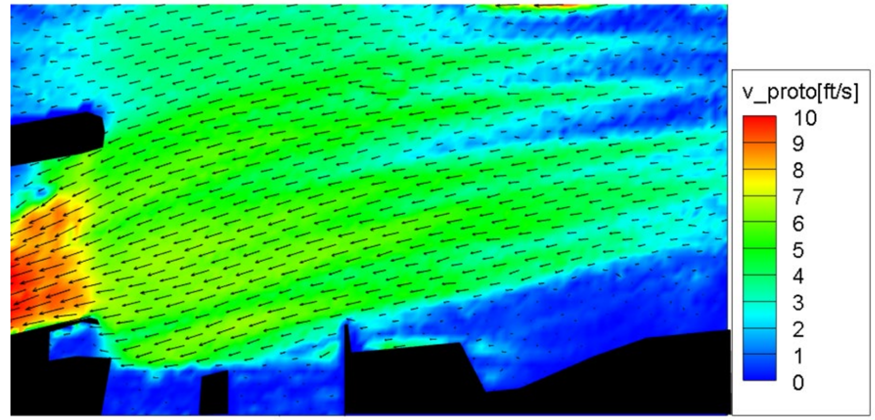


Figure C-11. Prototype velocity color map of surface velocities in area upstream of diversion entrance (bottom left) and hardened ramp (left) for MOD-9 design with flushing channel closed at 6,000 ft^3/s river flow.

Figure C-12. Views looking upstream from diversion canal of area upstream of diversion intake (bottom) and hardened ramp (left) for MOD-9 design with flushing channel closed at 6,000 ft^3/s river flow.

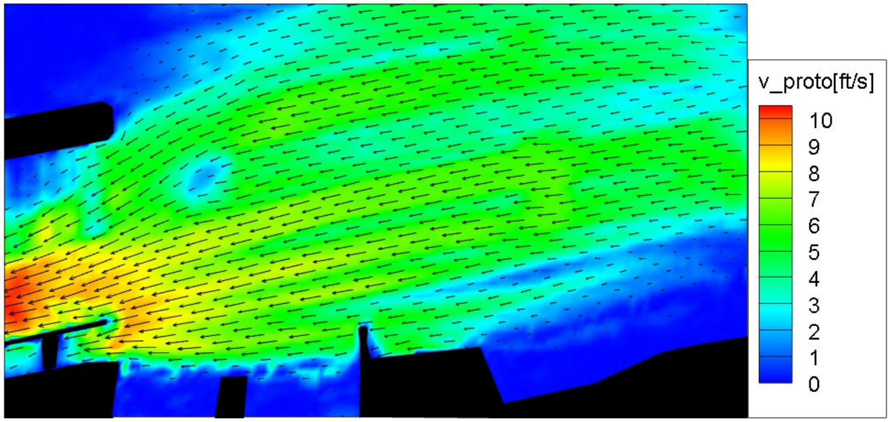


Figure C-13. Prototype velocity color map of surface velocities in area upstream of diversion entrance (bottom left) and hardened ramp (left) for MOD-6 design with flushing channel open at 6,000 ft^3/s river flow.


Figure C-14. Views looking upstream from diversion canal of area upstream of diversion intake (bottom) and hardened ramp (left) for MOD-6 design with flushing channel open at 6,000 ft^3/s.

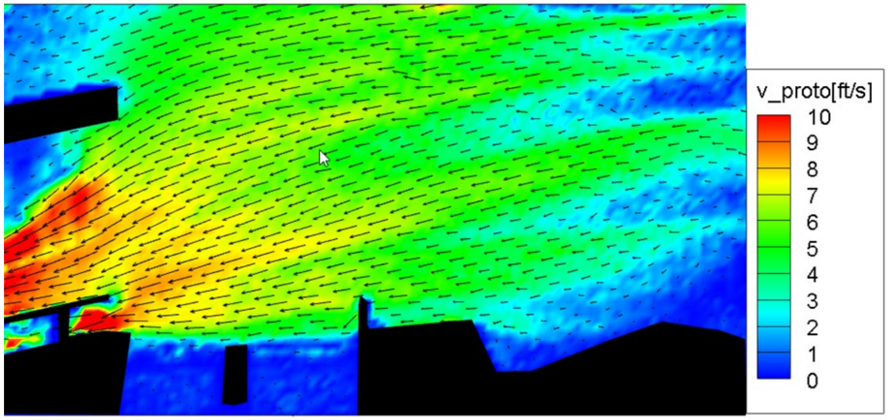


Figure C-15. Prototype velocity color map of surface velocities in area upstream of diversion entrance (bottom left) and hardened ramp (left) for MOD-9 design with flushing channel open at 6,000 ft3/s river flow.


Figure C-16. Views looking upstream from diversion canal of area upstream of diversion intake (bottom) and hardened ramp (left) for MOD-9 design with flushing channel open at 6,000 ft^3/s river flow.

River Flow 3,000 ft^3/s

MOD-6 Flushing Channel Closed

At 3,000 ft^3/s, the upstream portion of the model was submerged, and the dam crest was fully active. Coarse and fine sands moved down the main channel as a bed form which deposited in front of the intake gates and upstream end of the hardened ramp. Some sediment accrued on gate 2 of hardened ramp, leading into the low flow portion of the channel. No sediment accrued on gates 3-4 of the ramp, however the apron was covered by sediment. Additionally, sediment accrued in front of and partially up intake gates, however very little accumulated behind the gates in the intake

Downstream of the hardened ramp, the main flow path followed the left bank, leaving sand bars on the left over the hardened topography of the bank as well as on the right. On the hardened ramp, there was some sediment accumulation on the last three rows of baffles. However, these were not inundated and still had resting area available behind the baffles.

MOD-6 Flushing Channel Open

After the flushing channel was opened, the apron in front of flushing channel was immediately exposed. Flow split around the flushing channel wall caused turbulence at entrance, which enabled the flow to pull significant quantities of sediment. Very little sediment accumulated on the gates of the hardened ramp, however the apron in front of gate 3 to part of gate 4 was covered in sediment except for portion eroded by bullnose. Sediment remained relatively unchanged in front of the intake gates, except for gate 4 which was cleared.

Downstream of the flushing channel, significant scour occurred from the flushing channel to the end of the model. Sediment formations on the hardened ramp remained unchanged.

MOD-9 Flushing Channel Closed

At 3,000 ft^3/s, the upstream portion of the model was submerged, and the dam crest was fully active. As with the 6,000 ft^3/s MOD-9 configuration, very little sediment accumulated on the exit of the hardened ramp or in front of the intake, even though the riverbed was fully stabilized. The high point of the bedform was in front of the hardened ramp.

On the downstream portion of the hardened ramp, baffles on edge of transition with low flow channel partially filled in with sediment, however still area for resting behind baffles. This sediment deposition continued to the edge of the low flow portion of the hardened ramp. Scour was observed downstream of the low flow channel continuing to the end of the model extents.

MOD-9 Flushing Channel Open

After the flushing channel was opened, the riverbed shifted left towards the flushing channel. The highest point of the bedform was closer to the flushing channel as opposed to directly in front of the hardened ramp. As there was not significant sediment accumulation on the hardened ramp, this did not change once the flushing channel was opened. In front of the intake, gates 1 and 2 were cleared of sediment, while gates 3 and 4 remained relatively unchanged.

Downstream of the hardened ramp, the scour was behind the low flow channel, as opposed to the flushing channel. Sediment deposition patterns on the hardened ramp did not change from flushing channel closed configuration.

Figure C-17. View looking downstream after dewatering for MOD-6 design with flushing channel closed at 3,000 ft^3/s.

Figure C-18. View of ramp exit looking from left bank for MOD-6 design with flushing channel closed after 3,000 ft^3/s flow rate.

Figure C-19. View looking downstream after dewatering for MOD-9 design with flushing channel closed at 3,000 ft^3/s.

Figure C-20. View of ramp exit looking from left bank for MOD-9 design with flushing channel closed after 3,000 ft^3/s flow rate.

Figure C-21. View looking downstream after dewatering for MOD-6 design with flushing channel open at 3,000 ft^3/s.

Figure C-22. View of ramp exit looking from left bank for MOD-6 design with flushing channel open after 3,000 ft^3/s flow rate.

Figure C-23. View looking downstream after dewatering for MOD-9 design with flushing channel open at 3,000 ft^3/s.

Figure C-24. View of ramp exit looking from left bank for MOD-9 design with flushing channel open after 3,000 ft^3/s flow rate.

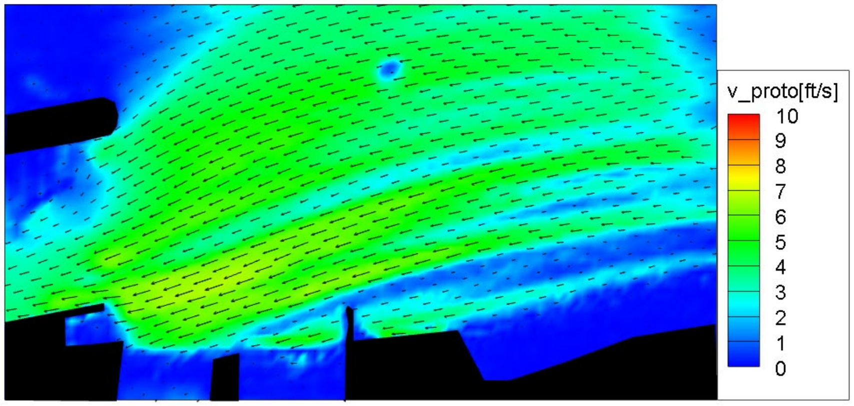


Figure C-25. Prototype velocity color map of surface velocities in area upstream of diversion entrance (bottom left) and hardened ramp (left) for MOD-6 design with flushing channel closed at 3,000 ft^3/s river flow.

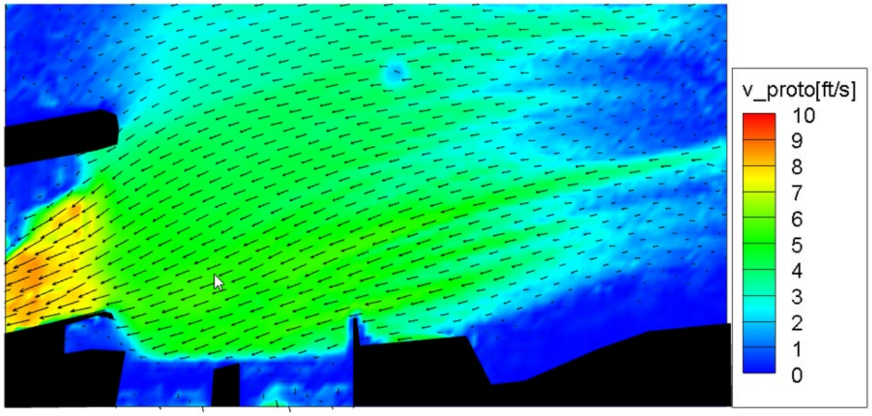


Figure C-27. Prototype velocity color map of surface velocities in area upstream of diversion entrance (bottom left) and hardened ramp (left) for MOD-9 design with flushing channel closed at 3,000 ft^3/s river flow.

Figure C-26. View looking upstream from diversion canal of area upstream of diversion intake (bottom) and hardened ramp (left) for MOD-6 design with flushing channel closed at 3,000 ft^3/s river flow.

Figure C-28. View looking upstream from diversion canal of area upstream of diversion intake (bottom) and hardened ramp (left) for MOD-9 design with flushing channel closed at 3,000 ft^3/s river flow.

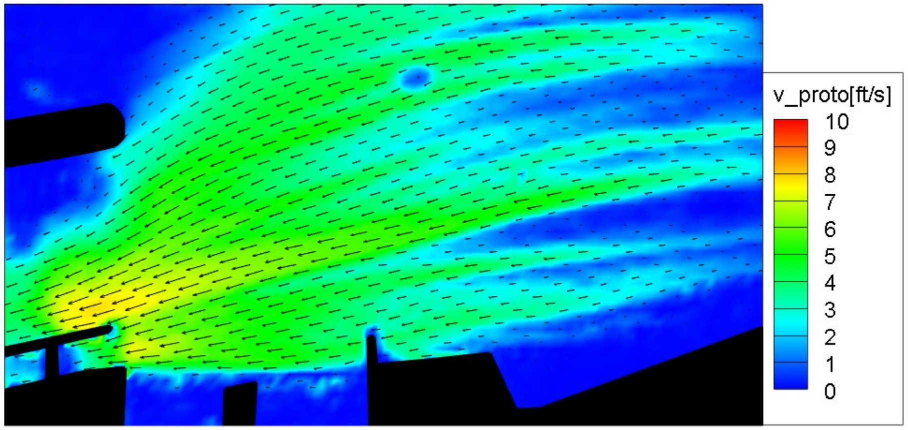


Figure C-29. Prototype velocity color map of surface velocities in area upstream of diversion entrance (bottom left) and hardened ramp (left) for MOD-6 design with flushing channel open at 3,000 ft^3/s river flow.

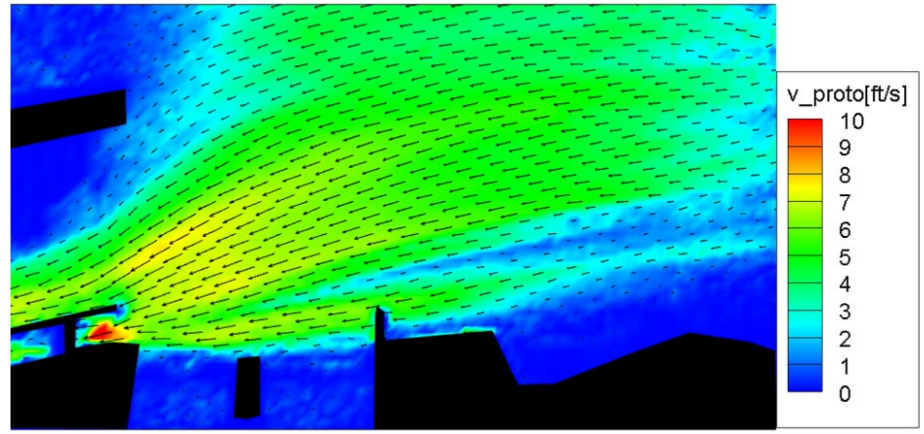


Figure C-31. Prototype velocity color map of surface velocities in area upstream of diversion entrance (bottom left) and hardened ramp (left) for MOD-9 design with flushing channel open at 3,000 ft^3/s river flow.

Figure C-30. View looking upstream from diversion canal of area upstream of diversion intake (bottom) and hardened ramp (left) for MOD-6 design with flushing channel open at 3,000 ft^3/s river flow.

Figure C-32. View looking upstream from diversion canal of area upstream of diversion intake (bottom) and hardened ramp (left) for MOD-9 design with flushing channel open at 3,000 ft^3/s river flow.

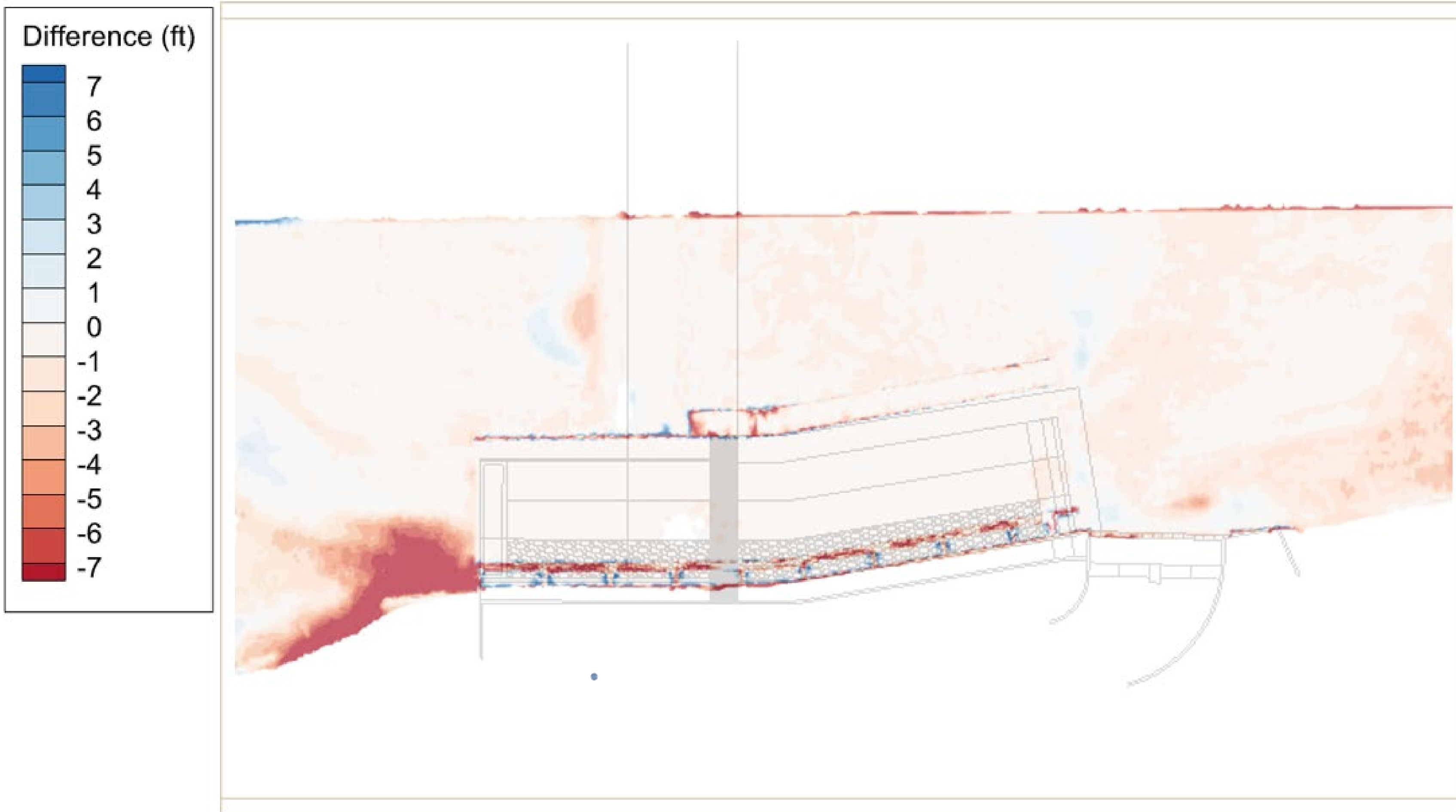


Figure C-33. Elevation difference map of 3,000 ft^3/s post-run bed elevations for MOD-6 with flushing channel closed compared to the 6,000 ft^3/s post-run bed elevations of MOD-6 with flushing channel closed. Flow is from right to left.

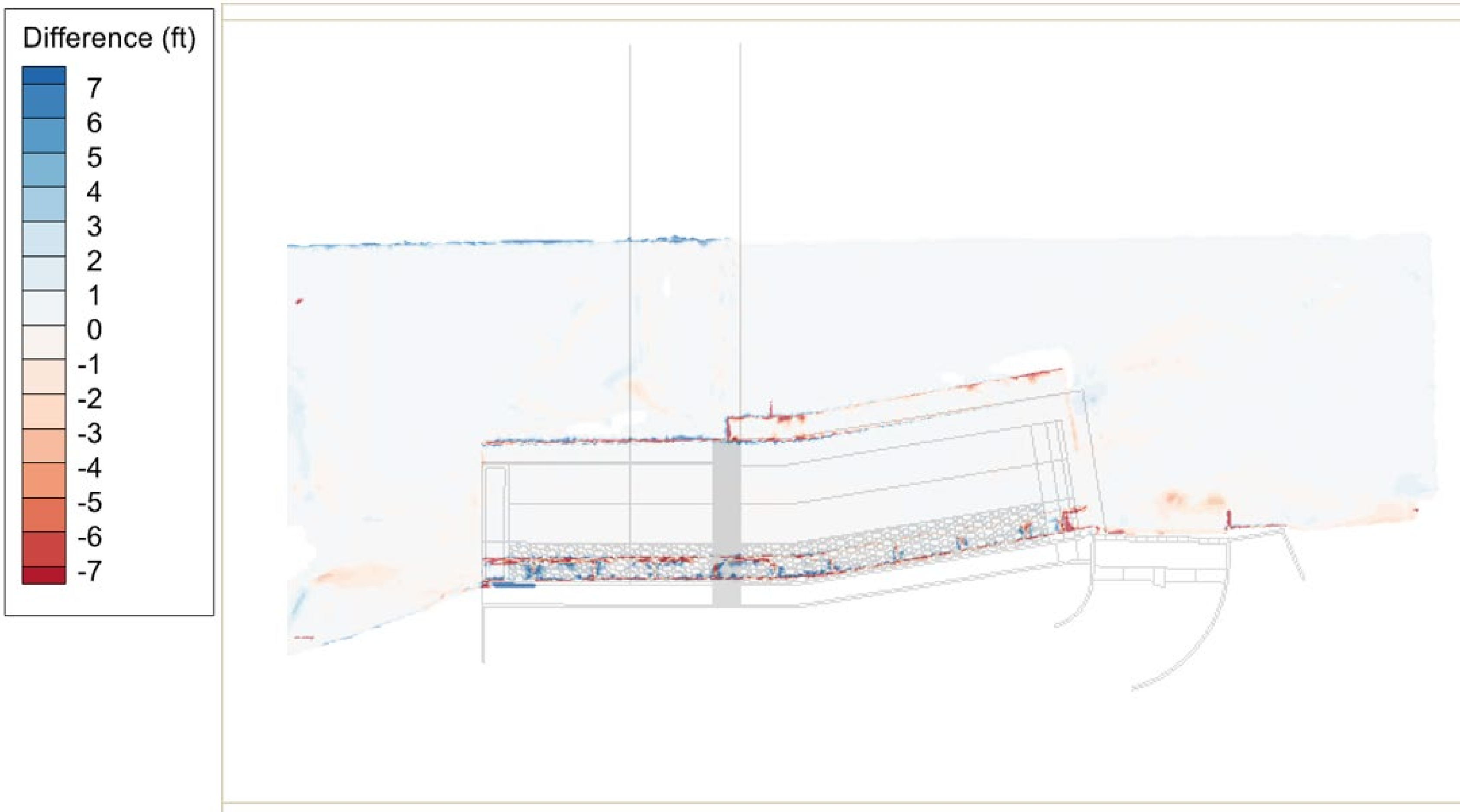


Figure C-34. Elevation difference map of 3,000 ft^3/s post-run bed elevations for MOD-9 with flushing channel closed compared to the 6,000 ft^3/s post-run bed elevations of MOD-9 with flushing channel closed. Flow is from right to left.

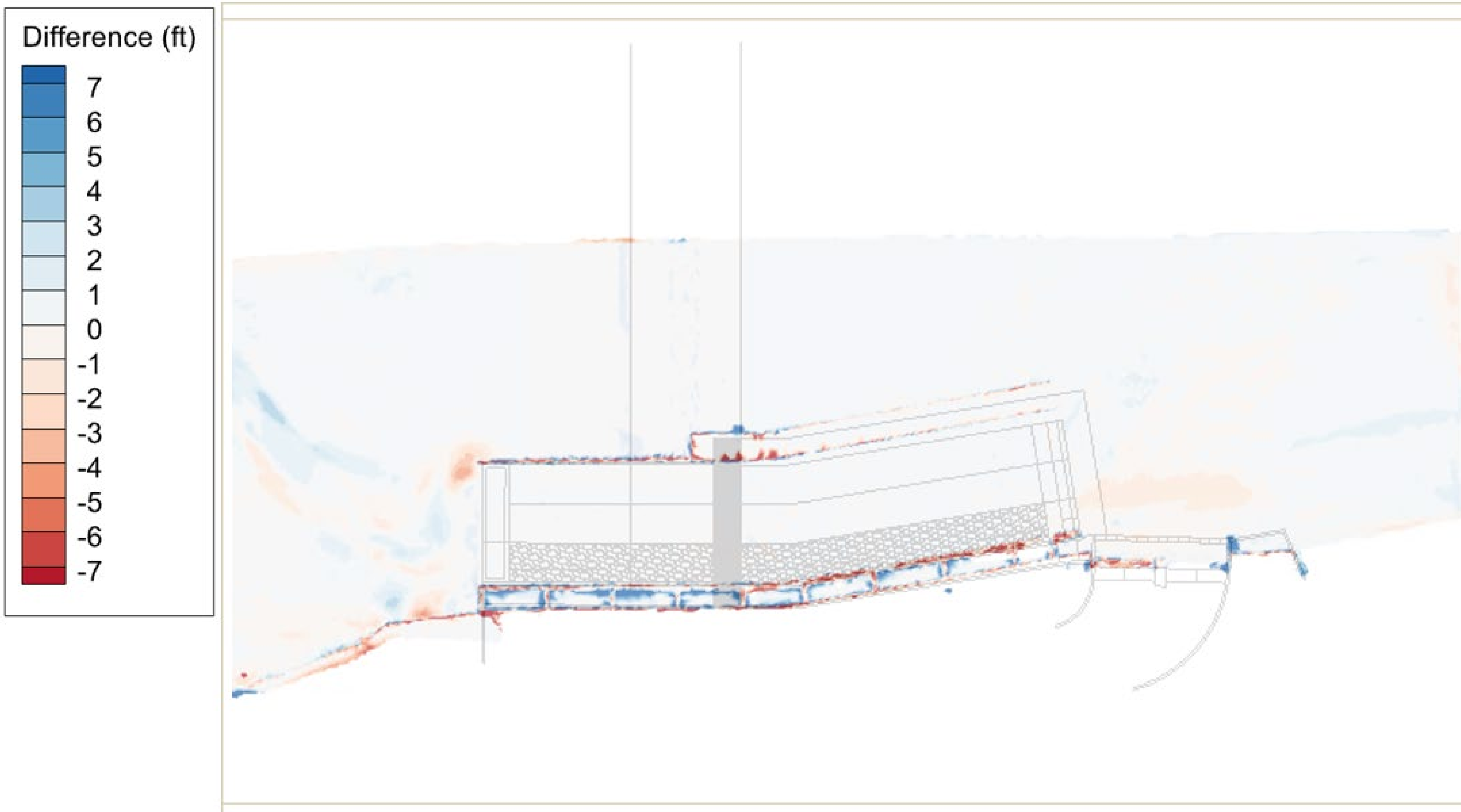


Figure C-35. Elevation difference map of 3,000 ft^3/s post-run bed elevations for MOD-6 with flushing channel open compared to the 6,000 ft^3/s post-run bed elevations of MOD-6 with flushing channel open. Flow is from right to left.

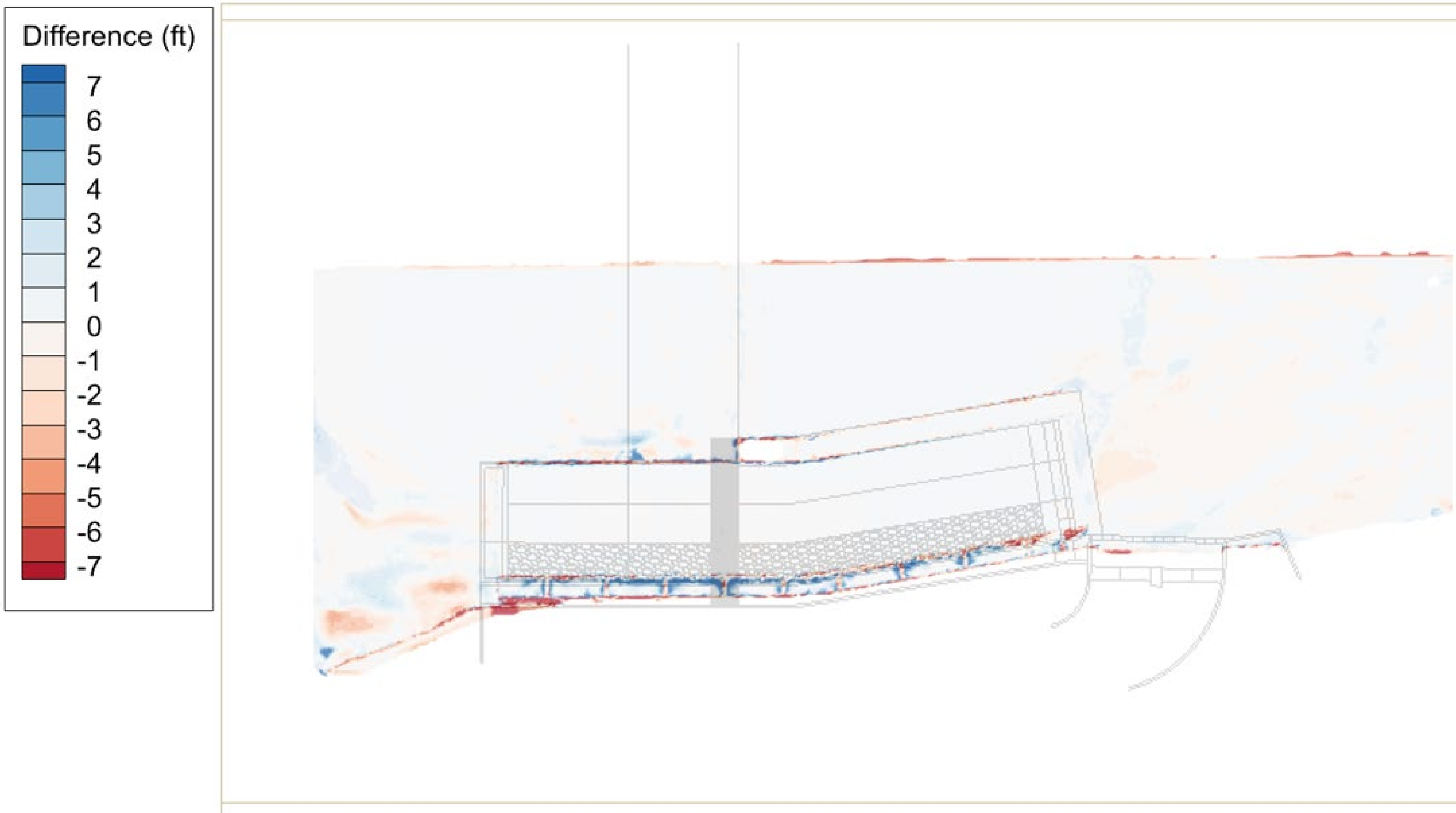


Figure C-36. Elevation difference map of 3,000 ft^3/s post-run bed elevations for MOD-9 with flushing channel open compared to the 6,000 ft^3/s post-run bed elevations of MOD-9 with flushing channel open. Flow is from right to left.

River Flow 1,500 ft^3/s

MOD-6 Flushing Channel Closed
At 1,500 ft^3/s, the dam crest was not active with all flow going down the intake or hardened ramp. Additionally, water depths in the river approaching the ramp and diversion were shallow and micro-channels within the main bedform began to develop. One side of the flow split went directly into diversion, with the other side going down the hardened ramp. No sediment accumulated on the gates of the hardened ramp, however the apron was fully covered and some sediment deposited on the upstream end of the low flow section of the hardened ramp. For the intake, minimal sediment accumulated on the gates, however more sediment was observed inside the intake than previous flows at this configuration. Diversion flow was able to reach 660 ft^3/s (less than the target of 825 ft^3/s) with all four intake gates fully open.

Downstream of the hardened ramp, sediment deposited in wave like pattern with scour still downstream of low flow channel of the hardened ramp. More sediment deposited on the baffled section of the hardened ramp and the transition area between the low flow channel and the baffled section. Most of the baffles remained dry at this flow rate, however the lower third of the ramp was submerged.

MOD-6 Flushing Channel Open
After the flushing channel was opened, all diversion flow from the intake was pulled down the hardened ramp, producing uniform sediment distribution on top of the intake gates. Sediment was lower in front of gates 3 and 4 on the intake apron than gates 1 and 2. As there was very little sediment accumulation on the hardened ramp during the flushing channel closed configuration, this did not change once the flushing channel was opened.

Downstream of the flushing channel, sediment formed a localized scour hole that did not continue to the extent of the model. Sediment accumulation did not change on the hardened ramp from the flushing channel closed configuration.

MOD-9 Flushing Channel Closed
At 1,500 ft^3/s, the dam crest was not active with all flow going down the intake or hardened ramp. Upstream of the hardened ramp, there was a slight flow split caused by shallow water depths going around the riverbed form, however some shallow sheet flow remained. No sediment accumulated on the gates or the low flow section of the hardened ramp. Sediment accumulated on all gates of the intake, however no sediment accrued in the downstream portion of the intake. Gates 3 and 4 had less sediment than 1 and 2. Diversion flow was able to reach 840 ft^3/s.

On the downstream portion of the hardened ramp, sediment deposition followed the submergence pattern. Almost the entire lower half of hardened ramp was submerged with significant deposition in the low flow channel. However, sediment deposition was not enough to bury the baffles. There was still scour downstream of the low flow section of the hardened ramp.

MOD-9 Flushing Channel Open
After the flushing channel was opened, the riverbed shifted left towards the flushing channel similar to previous tests. The highest point of the bedform was closer to the flushing channel as opposed to directly in front of the hardened ramp. Horseshoe shaped scour pattern developed around the left wall of the hardened ramp which caused some sediment to be cleared from intake gates 1 and 2 but did not affect sediment on the apron of the hardened ramp or the intake.

C-37. View looking downstream after dewatering for MOD-6 design with flushing channel closed at 1,500 ft^3/s.

Figure C-38. View of ramp exit looking upstream from left bank for MOD-6 design with flushing channel closed after 1,500 ft^3/s flow rate.

Figure C-39. View looking downstream after dewatering for MOD-9 design with flushing channel closed at 1,500 ft^3/s.

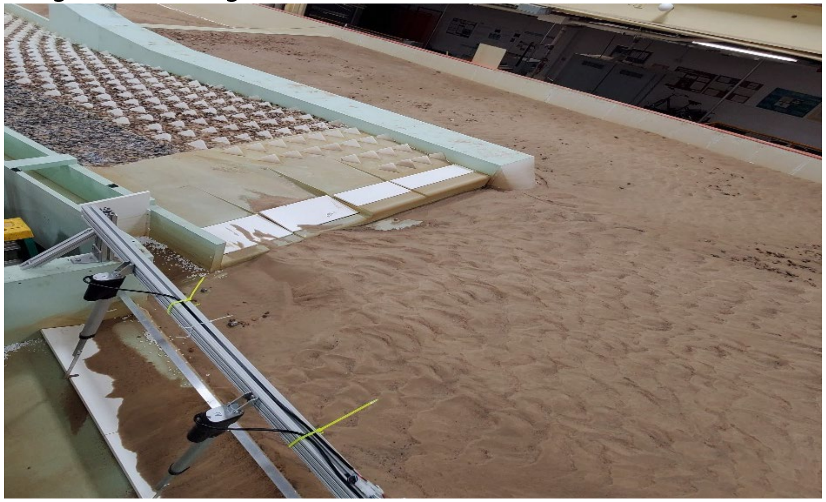


Figure C-40. View of ramp exit looking downstream from left bank for MOD-9 design with flushing channel closed after 1,500 ft^3/s flow rate.

Figure C-41. View looking downstream after dewatering for MOD-6 design with flushing channel open at 1,500 ft^3/s.

Figure C-42. View of ramp exit looking from left bank for MOD-6 design with flushing channel open after 1,500 ft^3/s flow rate.

Figure C-43. View looking downstream after dewatering for MOD-9 design with flushing channel open at 1,500 ft^3/s.

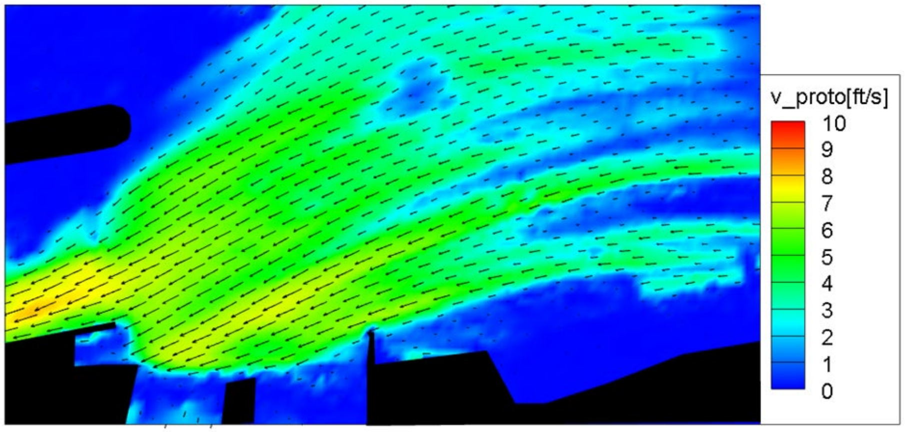


Figure C-44. Prototype velocity color map of surface velocities in area upstream of diversion entrance (bottom left) and hardened ramp (left) for MOD-6 design with flushing channel closed at 1,500 ft^3/s river flow.

Figure C-45. View looking upstream from diversion canal of area upstream of diversion intake (bottom) and hardened ramp (left) for MOD-6 design with flushing channel closed at 1,500 ft^3/s river flow.

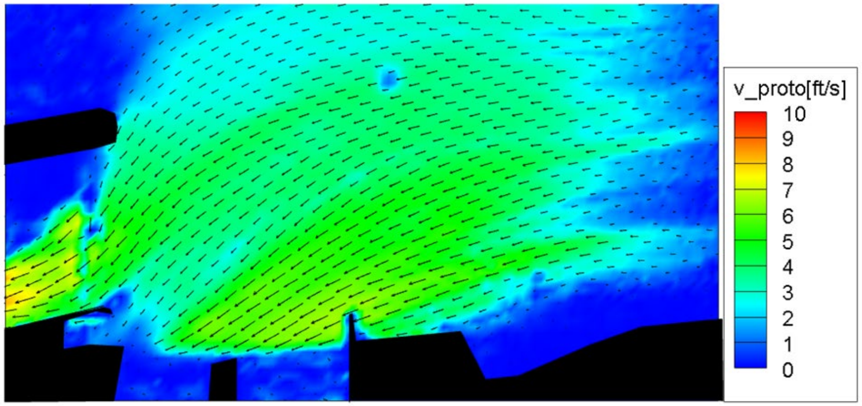


Figure C-46. Prototype velocity color map of surface velocities in area upstream of diversion entrance (bottom left) and hardened ramp (left) for MOD-9 design with flushing channel closed at 1,500 ft^3/s river flow.

Figure C-47. View looking upstream from diversion canal of area upstream of diversion intake (bottom) and hardened ramp (left) for MOD-9 design with flushing channel closed at 1,500 ft^3/s river flow.

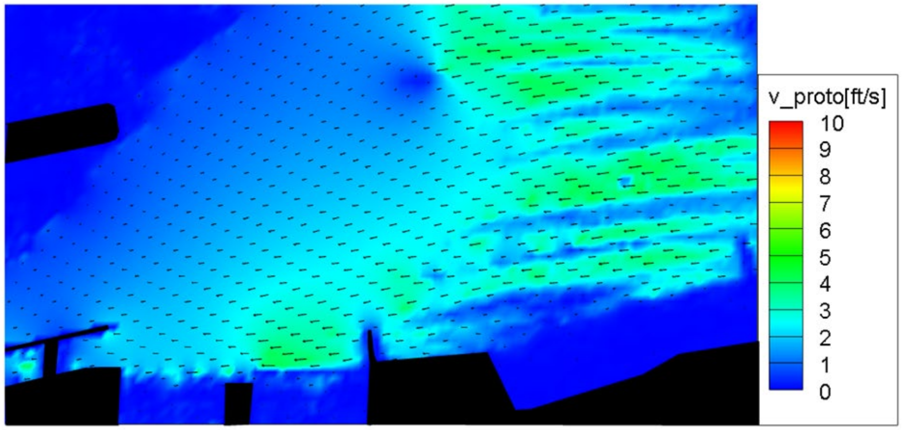


Figure C-48. Prototype velocity color map of surface velocities in area upstream of diversion entrance (bottom left) and hardened ramp (left) for MOD-6 design with flushing channel open at 1,500 ft^3/s river flow.

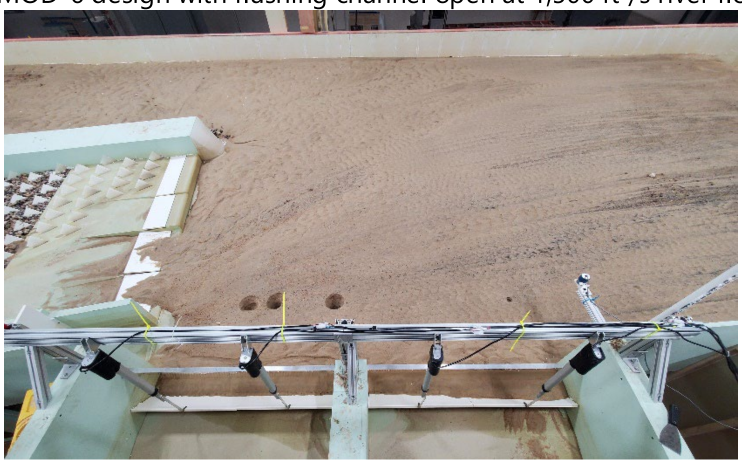


Figure C-49. View looking upstream from diversion canal of area upstream of diversion intake (bottom) and hardened ramp (left) for MOD-6 design with flushing channel open at 1,500 ft^3/s river flow.

Figure C-50. View looking upstream from diversion canal of area upstream of diversion intake (bottom) and hardened ramp (left) for MOD-9 design with flushing channel open at 1,500 ft^3/s river flow (PIV data not available).

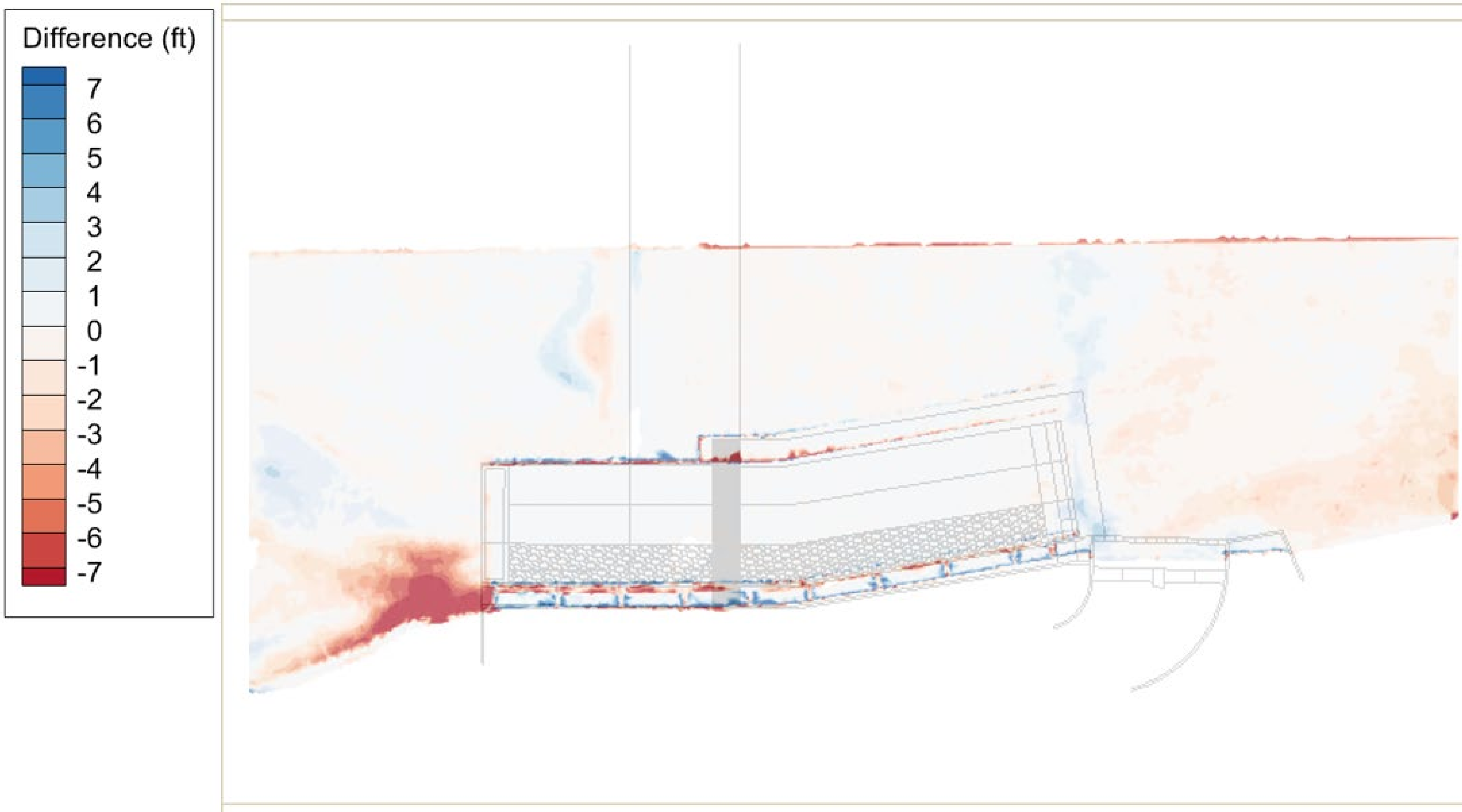


Figure C-51. Elevation difference map of 1,500 ft^3/s post-run bed elevations for MOD-6 with flushing channel closed compared to the 6,000 ft^3/s post-run bed elevations of MOD-6 with flushing channel closed. Flow is from right to left.

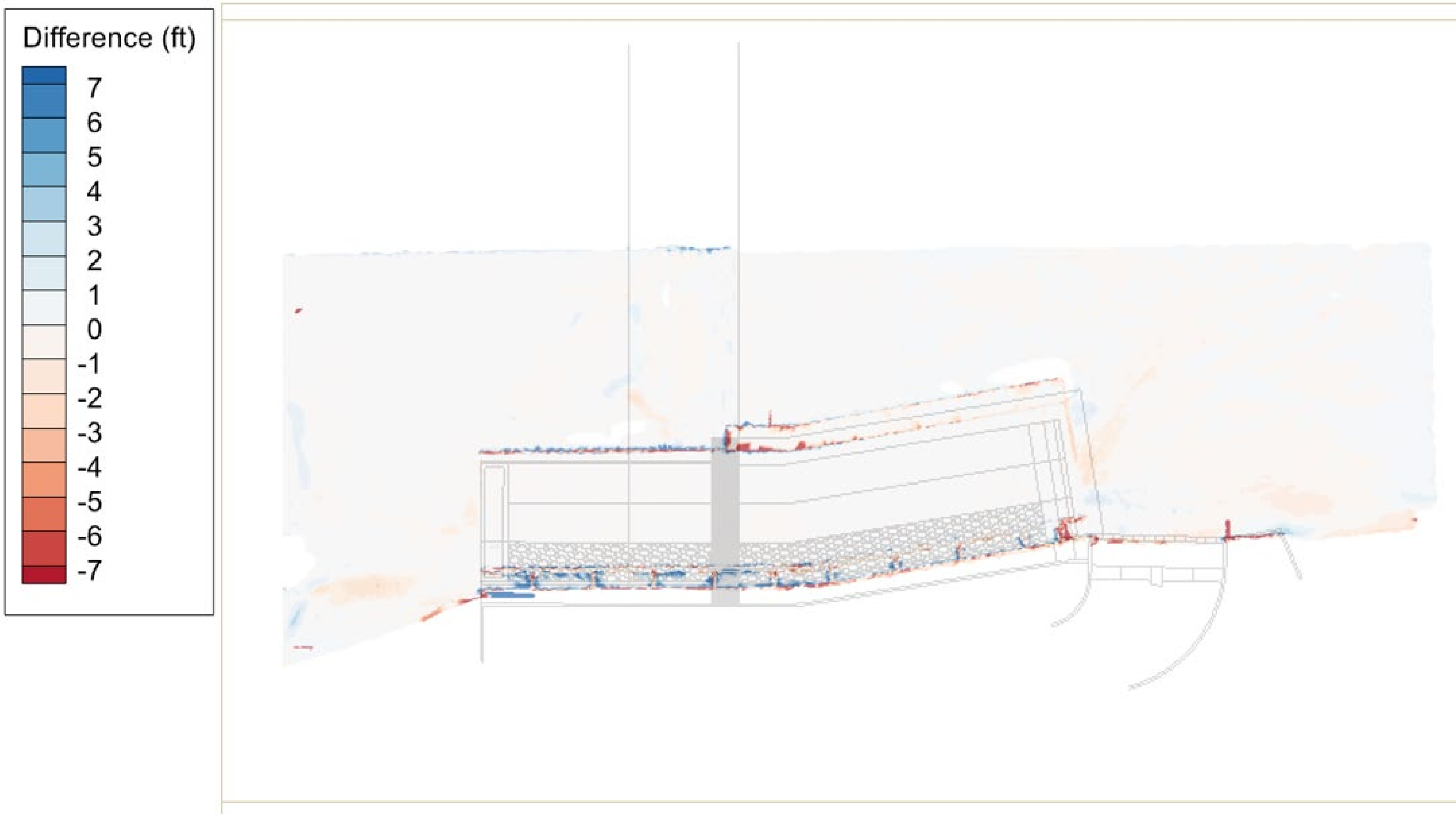


Figure C-52. Elevation difference map of 1,500 ft^3/s post-run bed elevations for MOD-9 with flushing channel closed compared to the 6,000 ft^3/s post-run bed elevations of MOD-9 with flushing channel closed. Flow is from right to left.

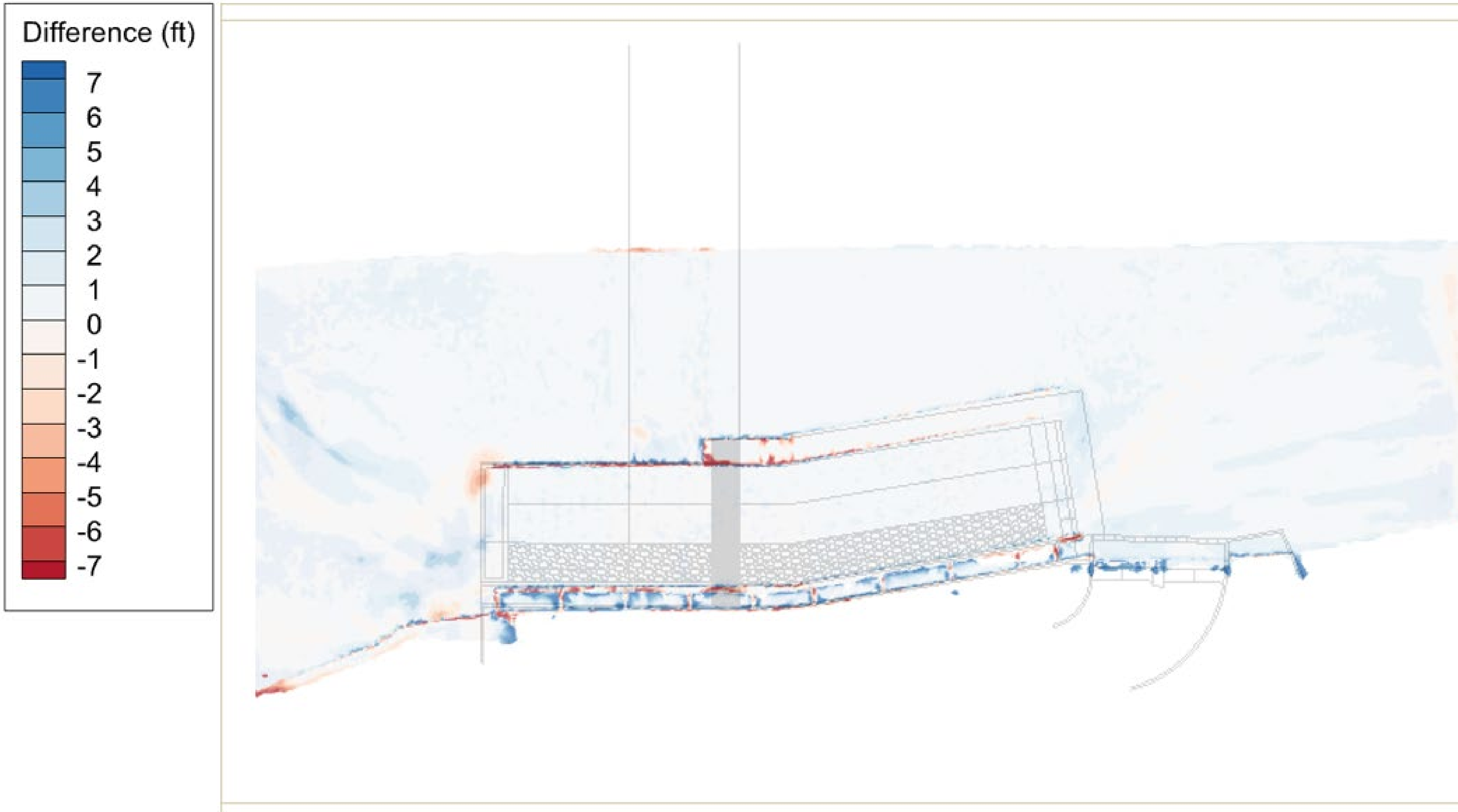


Figure C-53. Elevation difference map of 1,500 ft^3/s post-run bed elevations for MOD-6 with flushing channel open compared to the 6,000 ft^3/s post-run bed elevations of MOD-6 with flushing channel open. Flow is from right to left.

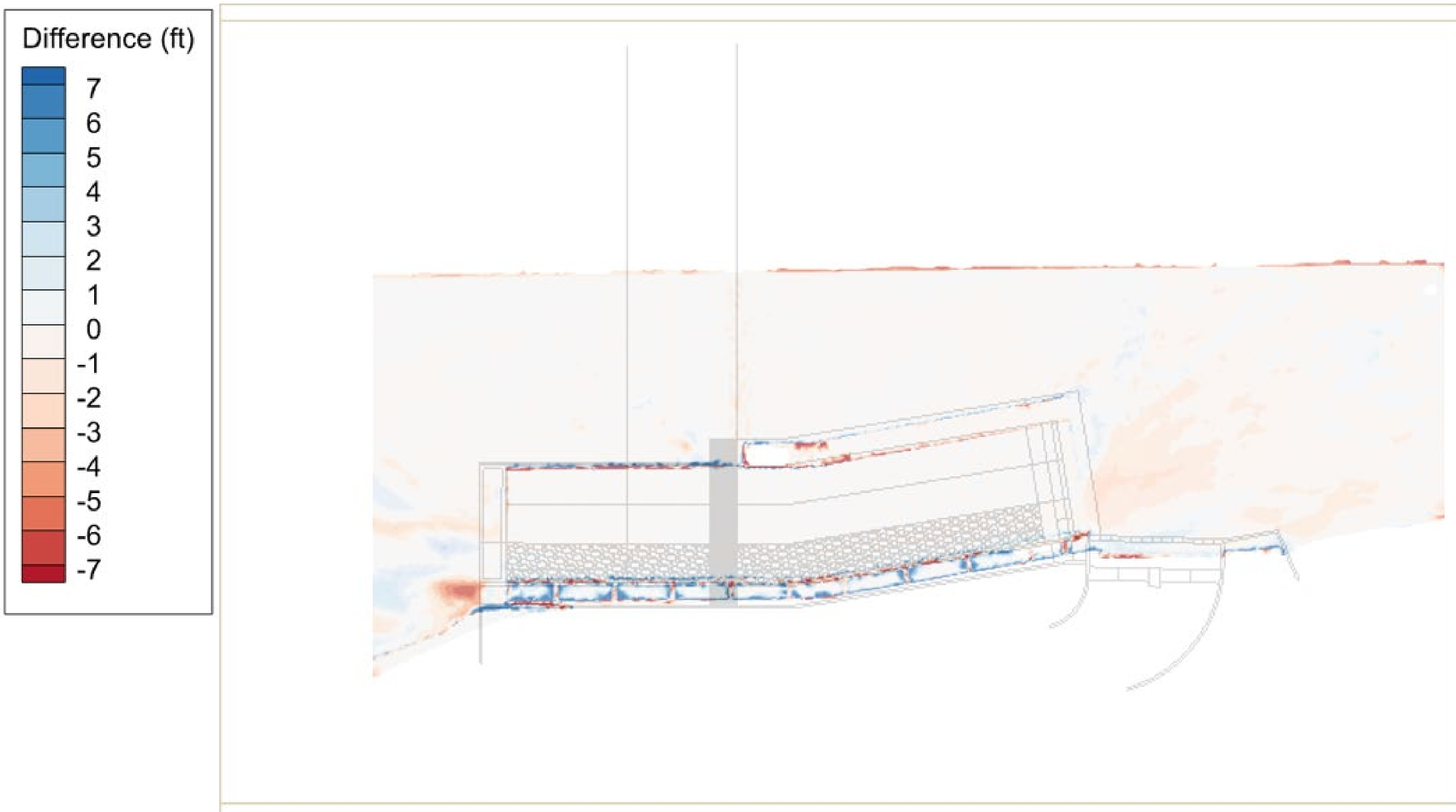


Figure C-54. Elevation difference map of 1,500 ft^3/s post-run bed elevations for MOD-9 with flushing channel open compared to the 6,000 ft^3/s post-run bed elevations of MOD-9 with flushing channel open. Flow is from right to left.

River Flow 270 ft^3/s

MOD-6 Flushing Channel Closed

At 270 ft^3/s, the dam crest was not active with all flow going down the intake or hardened ramp. Additionally, water depths in the river were so shallow, flow split around riverbed form. One side of the flow split went directly into diversion, with the other side going down the hardened ramp. Flow would approach directly upstream of the bullnose and then curve to enter the hardened ramp at gates 2 and 3. Sediment accumulated on the throughout the hardened ramp apron with some additional sediment on gates 1 and 2. Due to the other side of the flow split approaching the intake, sediment was lower in front of all of the gates. Compared to the bedform upstream of the hardened ramp. Diversion flow was able to reach 54 ft^3/s (target of 110 ft^3/s) with all four of the intake gates fully open.

On the downstream portion of the hardened ramp, more sediment accumulated in the low flow section than the baffled area. The lower third of the hardened ramp was submerged, with large dead zones of flow in the baffled area. Scour was observed downstream of the hardened ramp.

MOD-6 Flushing Channel Open

After the flushing channel was opened, all flow originally going into the intake was diverted into the flushing channel. The flow split observed in the flushing channel closed configuration was still present, however as flow was drawn away from the intake, more flow went down gate 1 of the hardened ramp. As such, the low flow section of the hardened ramp had some sediment accumulate as an extension of the riverbed. Sediment was removed directly upstream of the flushing channel, however sediment in front of the intake remained unchanged, except for gate 4.

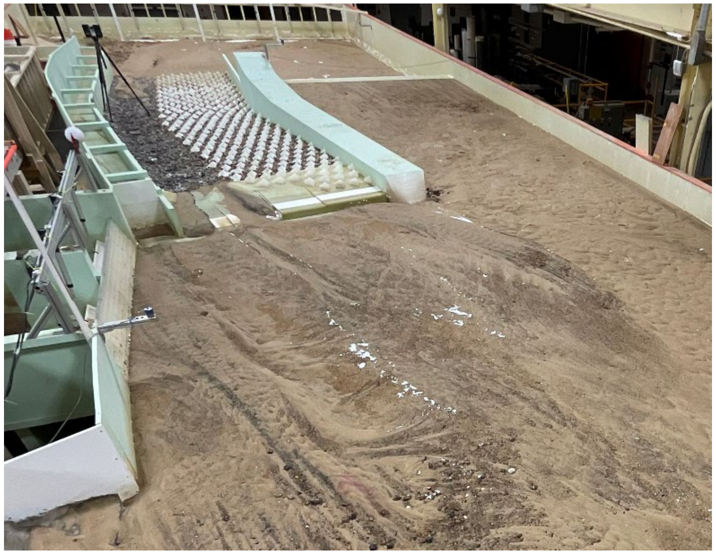
On the downstream portion of the hardened ramp, sediment continued to accumulate in the low flow section for the lower half of the ramp. Sediment in the baffled section deposited mainly along the transition from the low flow section. None of the baffles were completely covered by the sediment. Scour remained downstream of the flushing channel.

MOD-9 Flushing Channel Closed

At 270 ft^3/s, the dam crest was not active with all flow going down the intake or hardened ramp. Additionally, water depths in the river were so shallow, flow split around riverbed form. One side of the flow split went mostly into diversion, with the other side going down the hardened ramp. No sediment accumulated on the gates of the hardened ramp, with very little sediment accumulating at the exit to the low flow section. Due to the approach of the flow split, sediment was lower in front of intake gates 3 and 4 compared to gates 1 and 2. All intake gates had some sediment accrue on top. Diversion flow was able to reach 110 ft^3/s.

MOD-9 Flushing Channel Open

At this low flow there was little influence on the upstream bedform and flow patterns by opening the flushing channel. The microchannel on the left side of the bedform was directed to the flushing channel and along the intake apron. The one on the right continued to flow into gate 1 and the low flow section of the hardened ramp. There were minimal changes observed to the upstream bedforms.



C-55. View looking downstream after dewatering for MOD-6 design with flushing channel closed at 270 ft^3/s.

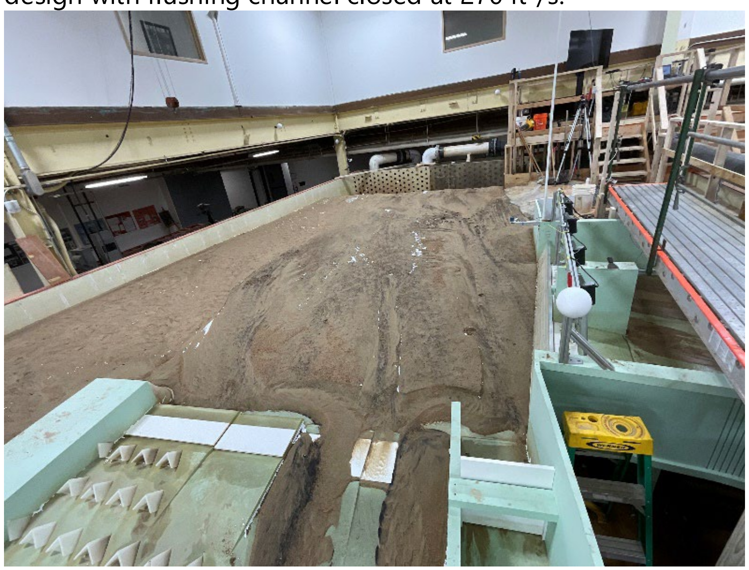


Figure C-56. View looking upstream for MOD-6 design with flushing channel closed after 270 ft^3/s flow rate.

Figure C-57. View looking downstream after dewatering for MOD-6 design with flushing channel open at 270 ft^3/s. The black features on top of the bedform are iron deposits from the sediment blend and are not larger cobble sized material.

Figure C-58. View looking upstream for MOD-6 design with flushing channel open after 270 ft^3/s flow rate.

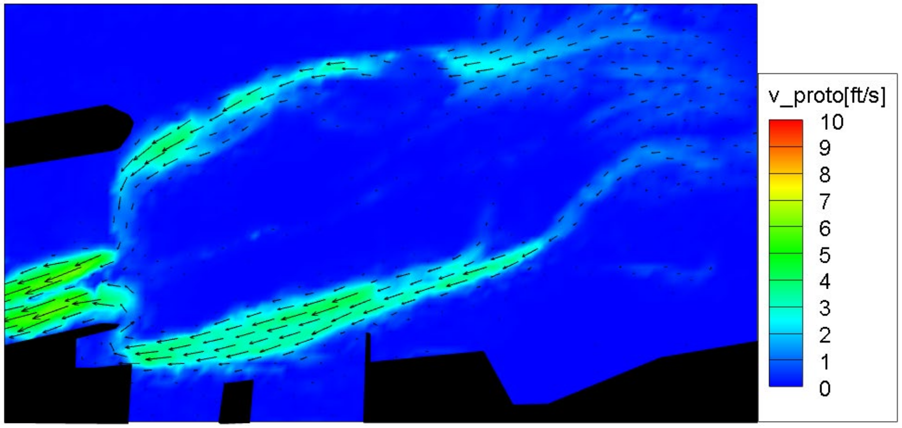


Figure C-59. Prototype velocity color map of surface velocities in area upstream of diversion entrance (bottom left) and hardened ramp (left) for MOD-6 design with flushing channel closed at 270 ft^3/s river flow.

Figure C-60. View looking upstream from diversion canal of area upstream of diversion intake (bottom) and hardened ramp (left) for MOD-6 design with flushing channel closed at 270 ft^3/s river flow.

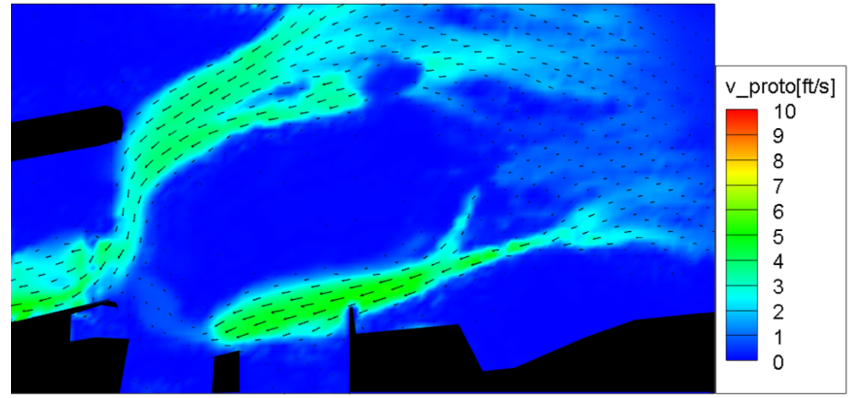


Figure C-61. Prototype velocity color map of surface velocities in area upstream of diversion entrance (bottom left) and hardened ramp (left) for MOD-9 design with flushing channel closed at 270 ft^3/s river flow.

Figure C-62. View looking upstream from diversion canal of area upstream of diversion intake (bottom) and hardened ramp (left) for MOD-9 design with flushing channel closed at 270 ft^3/s river flow.

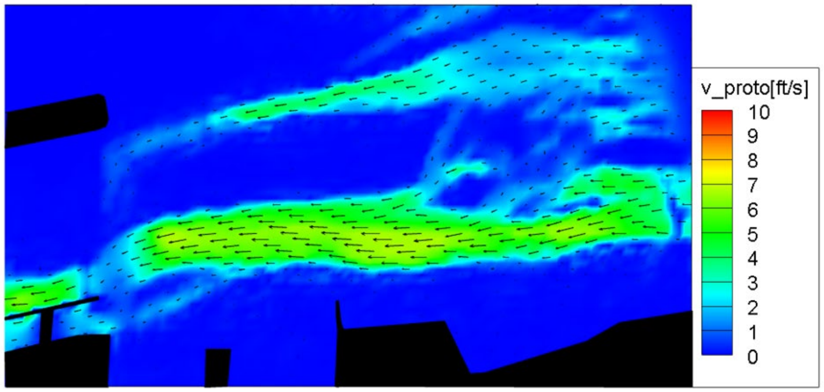


Figure C-63. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-6 design with flushing channel open at 270 ft^3/s river flow.

Figure C-64. Views looking upstream from diversion canal of area upstream of diversion intake (bottom) and hardened ramp (left) for MOD-6 design with flushing channel open at 270 ft^3/s river flow.

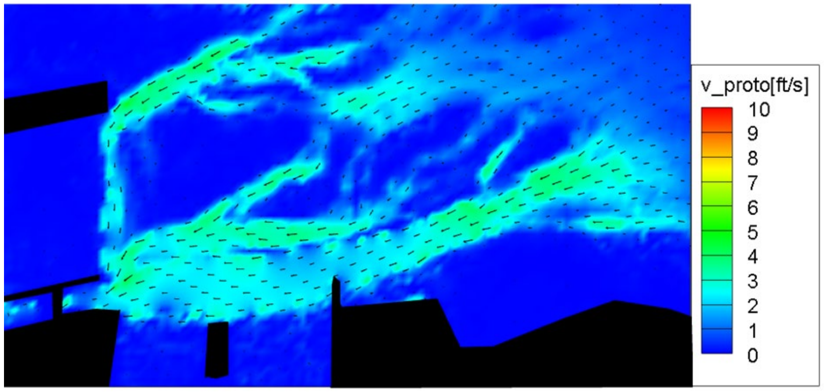


Figure C-65. Prototype velocity color map of surface velocities in area upstream of diversion entrance (left) and hardened ramp (right) for MOD-9 design with flushing channel open at 270 ft^3/s river flow (photo unavailable).

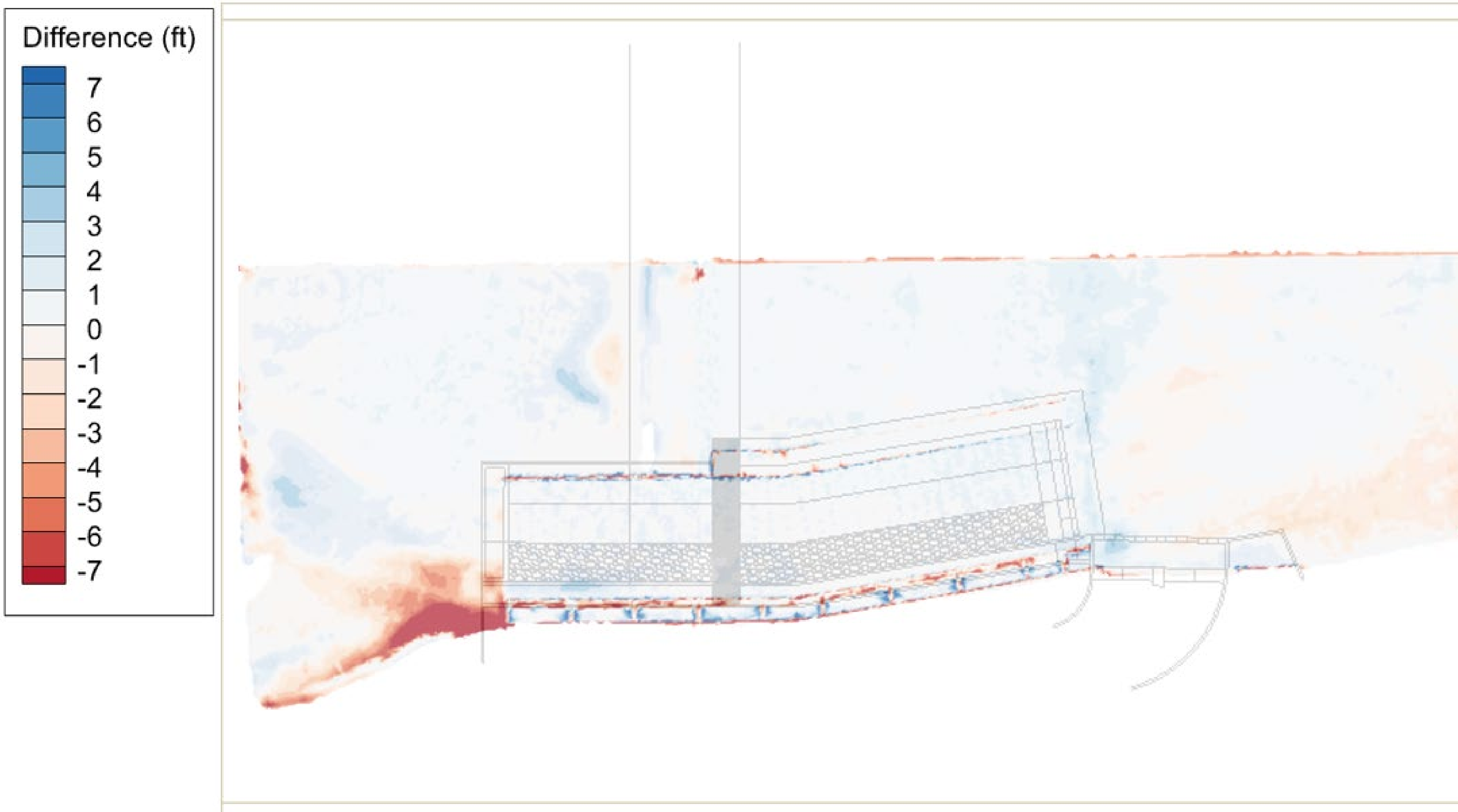


Figure C-66. Elevation difference map of 270 ft^3/s post-run bed elevations for MOD-6 with flushing channel closed compared to the 6,000 ft^3/s post-run bed elevations of MOD-6 with flushing channel closed. Flow is from right to left.

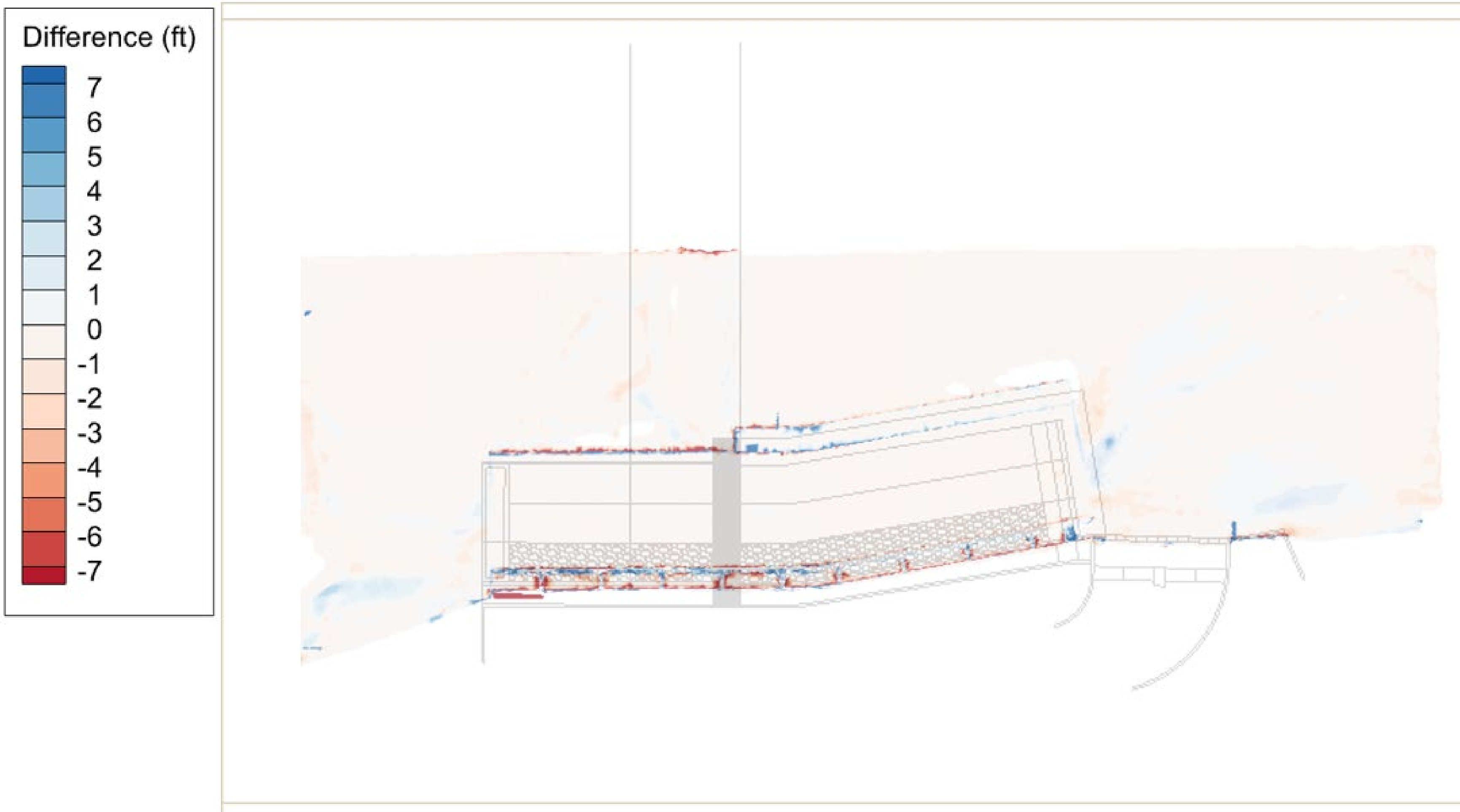


Figure C-67. Elevation difference map of 270 ft^3/s post-run bed elevations for MOD-9 with flushing channel closed compared to the 6,000 ft^3/s post-run bed elevations of MOD-9 with flushing channel closed. Flow is from right to left.

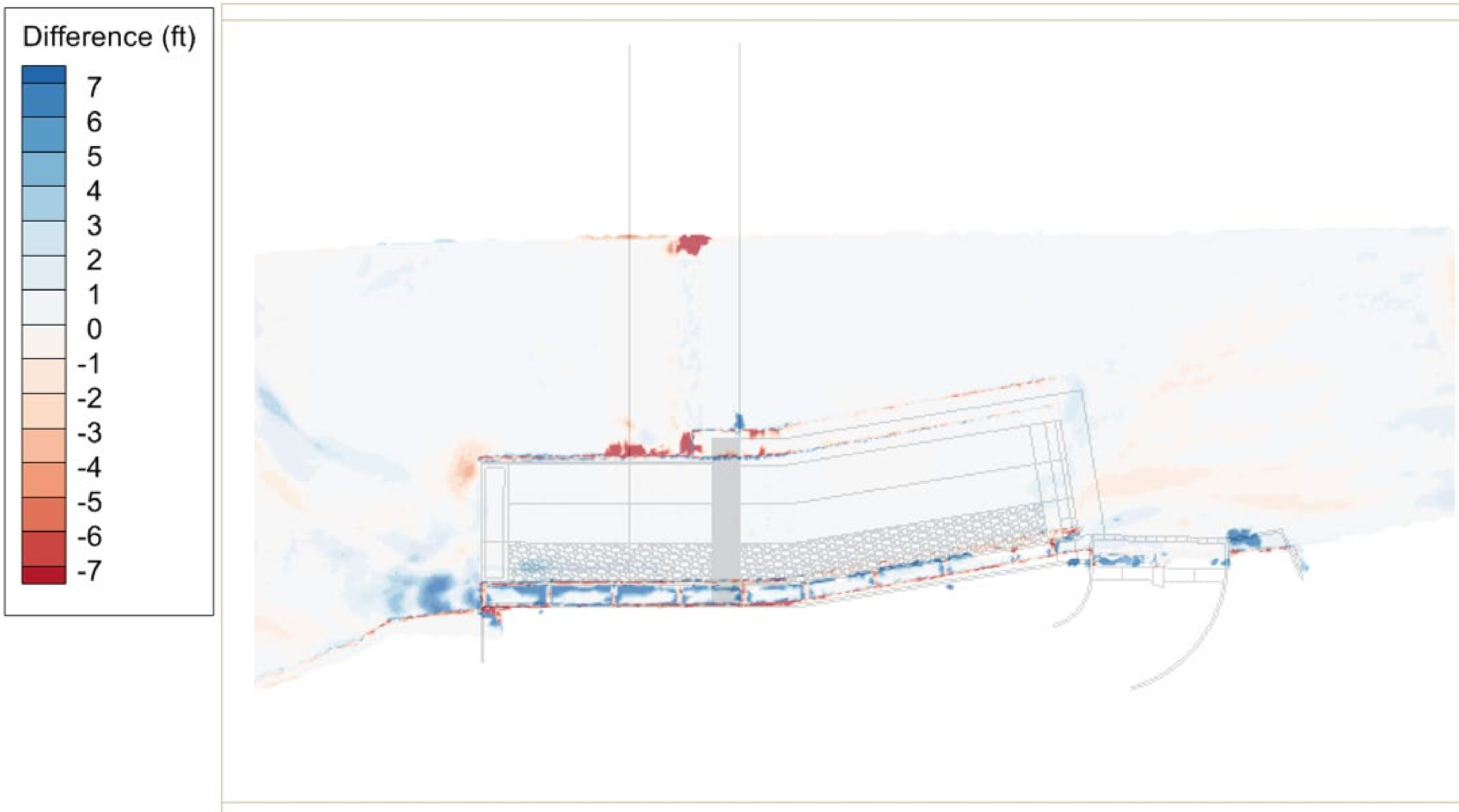


Figure C-68. Elevation difference map of 270 ft^3/s post-run bed elevations for MOD-6 with flushing channel open compared to the 6,000 ft^3/s post-run bed elevations of MOD-6 with flushing channel open. Flow is from right to left.

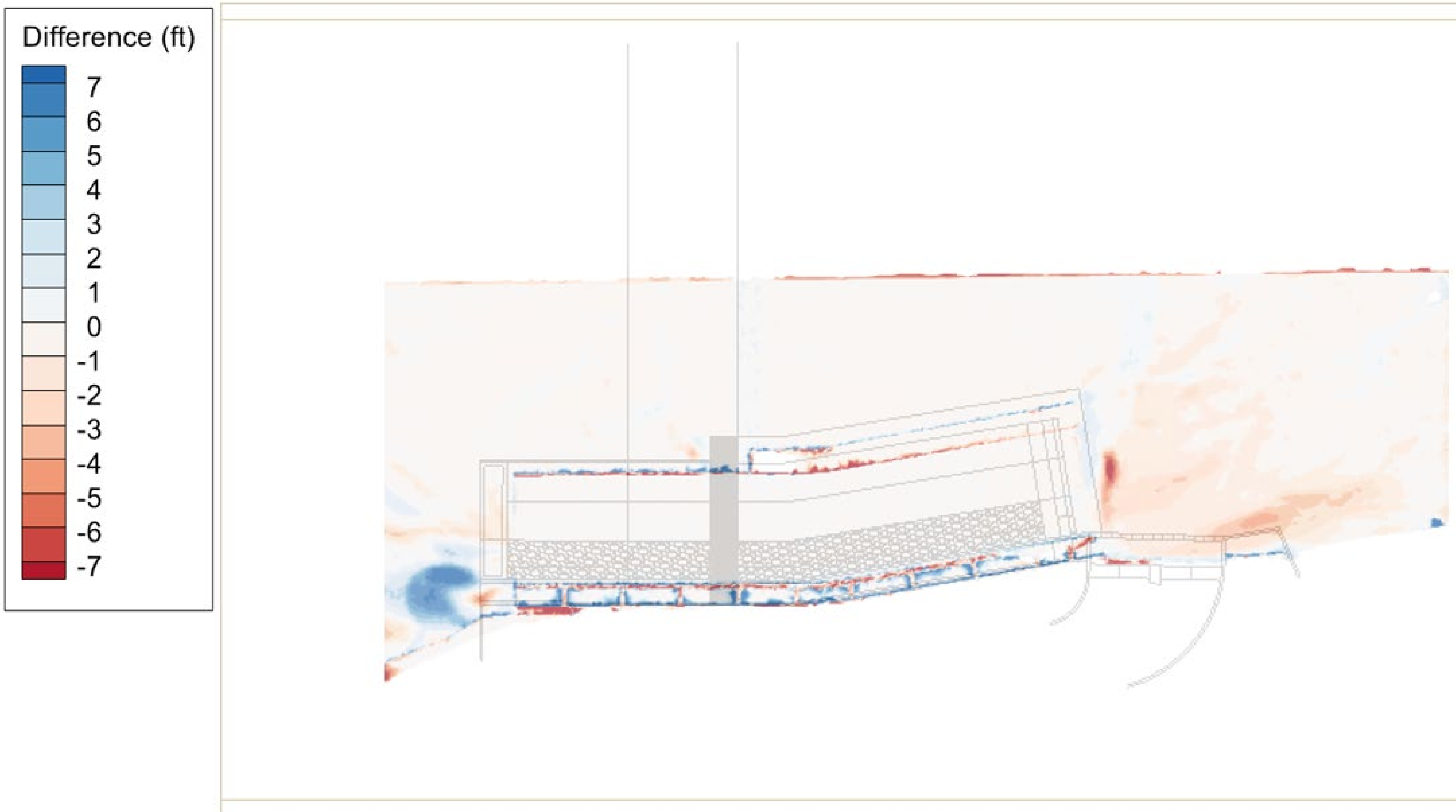


Figure C-69. Elevation difference map of 270 ft^3/s post-run bed elevations for MOD-9 with flushing channel open compared to the 6,000 ft^3/s post-run bed elevations of MOD-9 with flushing channel open. Flow is from right to left.

Comparison of MOD-6 and MOD-9 Design Configurations

Key points summarizing the comparison of MOD-6 and MOD-9 are given below:

- A significant bedform developed and stabilized in the area immediately upstream of the hardened ramp and canal intake. Sediment deposited on the upstream end of the hardened ramp and onto the canal intake gates. This formation occurred for both MOD-6 and MOD-9 design configurations and was repeatable for all discharges tested.
- All diversion discharge targets were achieved at MOD-9. MOD-6 was not able to divert the desired target river flows of 270 and 1,500 ft^3/s. In the MOD-6 configuration the max diversion with the canal intake gates fully lowered was only 54 ft^3/s (target of 110 ft^3/s) and 660 ft^3/s (target of 825 ft^3/s) at river flows of 270 ft^3/s and 1,500 ft^3/s respectively. This was due to the lower water surface elevations at the canal intake from the MOD-6 design.
- The flushing channel was ineffective at removing sediment from in front of the intake at both MOD-6 and MOD-9.
- There was significant flow separation from the bullnose on the ramp wall into the hardened ramp for every configuration that was tested. Surface velocity results showed slightly higher velocities for MOD-6 upstream of the hardened ramp which is to be expected with lower water depths compared to MOD-9 and the steeper gradient of the river to meet the top of the ramp.
- For both design configurations, at decreasing discharges the primary flow channel was reduced in size and then formed microchannels flowing toward the canal intake and the left side of the hardened ramp that was lowest in elevation.
- On the upstream end of the hardened ramp, MOD-9 had less sediment accumulation than MOD-6. PIV results showed slightly higher velocities for MOD-6 upstream of the hardened ramp which is to be expected with lower water depths compared to MOD-9. However, once flow passed into the low flow section of the hardened ramp, MOD-9 showed higher surface velocities than MOD-6.
- Within the downstream end of the hardened ramp, both MOD-6 and MOD-9 experienced sediment deposition on the downstream end of the hardened ramp, especially behind the baffles. However, sediment in the MOD-6 configuration completely covered the baffles on the downstream portion of the ramp. MOD-9 still had available resting areas behind the baffles.
- Sediment deposition patterns on the downstream end of the hardened ramp varied between MOD-6 and MOD-9. For MOD-9, a shear zone formed off the right wall about midway down the ramp where it angles to the right. This produced a low velocity region downstream along the right side of the ramp which created a diagonal sandbar from the baffled section to the low flow section. Deposition in this area also occurred for MOD-6 although specific patterns and locations varied to a minor degree.
- While the area downstream of the hardened ramp was influenced by the close proximity to the model exit, flow patterns at the downstream end of the hardened ramp were very similar for both configurations over the range of discharges tested. In general, flow exiting the ramp

paralleled the topography of the left bank and dispersed uniformly as it moved downstream. Subsequent sediment bedforms downstream were similar overall with scour downstream of the low flow section of the hardened ramp.

- Since a significant bedform developed for both MOD-6 and MOD-9 design configurations and MOD-6 was not capable of achieving the target diversion flows, design development focused on MOD-9 design.

Appendix C-1: Detailed Physical Model Observations

Table C-1. Model observations for MOD-6 design with flushing channel closed and open at 270 ft^3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-6 Flushing Channel Closed**	• No flow over dam crest. Some dead flow around bull nose, but no water near dam.
	MOD-6 Flushing Channel Open	• No flow over dam crest.
Upstream of Hardened Ramp	**MOD-6 Flushing Channel Closed**	• Flow split around upstream bedform (not enough water to overtop sediment accumulation in front of hardened ramp). Flow parallel to bullnose until a few feet upstream, then curves around and enters through gates 2-3. • Some sediment on all of apron with some up on gates 1-2 and in low flow channel.
	MOD-6 Flushing Channel Open	• Flow split seen in flushing channel closed continues to play significant effect on sediment pattern. • Some sediment accumulation on gates 1-2, low flow channel, and all of apron.
Upstream of Diversion Intake	**MOD-6 Flushing Channel Closed**	• Other side of flow split described upstream of hardened ramp entirely towards intake gates, causing low point of sediment in front of intake.
	MOD-6 Flushing Channel Open	• All flow diverted from intake into flushing channel. • Sediment removed from area going down flushing channel, however as this is not immediately in front of the gates, the sediment remains on the apron/gates of intake.
Downstream of Hardened Ramp	**MOD-6 Flushing Channel Closed**	• Sediment deposition in a wave pattern downstream of hardened ramp with scour hole behind low flow channel. • Sediment on last few rows of baffles by transition to low flow channel. Additional sediment accumulation in low flow channel. Lower 1/3 of channel submerged with large areas of no flow.
	MOD-6 Flushing Channel Open	• Sediment deposited in transverse pattern on lower half of hardened ramp and low flow channel. However, baffles are not fully covered by sediment, with space for resting remaining behind the baffles. • Scour behind flushing channel, rest of the sediment deposited evenly downstream of hardened ramp.

Table C-2. Model observations for MOD-9 design with flushing channel closed and open at 270 ft^3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-9 Flushing Channel Closed**	• Same as MOD-6, no flow over dam crest but some water around right side of bullnose.
	MOD-9 Flushing Channel Open	• No flow over crest.
Upstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• Flow split around upstream bedform (not enough water to overtop sediment accumulation in front of hardened ramp). Flow parallel to bullnose until a few feet upstream, then curves around and enters through gates 1-3. • Some sediment on all of apron with some up on gates 1-2 and in low flow channel.
	MOD-9 Flushing Channel Open	• Microchannel on left shifts to the flushing channel inlet. The one on the right goes to gate 1 of hardened ramp
Upstream of Diversion Intake	**MOD-9 Flushing Channel Closed**	• Other side of flow split described upstream of hardened ramp entirely towards intake gates, causing low point of sediment in front of intake. • More sediment on intake gates 1-2 than 3-4, however still on all gates.
	MOD-9 Flushing Channel Open	• Microchannel on left shifts to the flushing channel inlet. The one on the right goes to gate 1 of hardened ramp
Downstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• Sediment from previous flow rates remain, however it does not appear as though any new sediment accumulates. • Slightly less sediment in the low-flow channel than in MOD-6, this differs from 1500 ft^3/s where MOD-9 had more sediment in the low flow channel. • Downstream of hardened ramp had large scour hole downstream of the flushing channel.

Table C-3. Model observations for MOD-6 design with flushing channel closed and open at 1,500 ft^3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-6 Flushing Channel Closed**	• No flow over dam crest. Some water following right wall of hardened ramp, but not enough to activate crest.
	MOD-6 Flushing Channel Open	• No flow over dam crest. Some flow accumulation perpendicular to bull nose, however none approached the crest.
Upstream of Hardened Ramp	**MOD-6 Flushing Channel Closed**	• Flow split around upstream bedform (not enough water to overtop sediment accumulation in front of hardened ramp). Flow parallel to bullnose until a few feet upstream, then curves around and enters through gates 2-3. Sediment on apron in front of gates 1-2 and in low flow channel. • Other side of flow split entirely towards the intake gates.
	MOD-6 Flushing Channel Open	• All flow from canal intake pulled down flushing channel. • Sediment on hardened ramp apron with some on gates 1-2 in front of the low flow channel.
Upstream of Diversion Intake	**MOD-6 Flushing Channel Closed**	• Other side of flow split described upstream of hardened ramp entirely towards intake gates. Entire apron filled in with sediment.
	MOD-6 Flushing Channel Open	• All flow from canal intake pulled down flushing channel. • Uniform sediment distribution across intake gates and on apron.
Downstream of Hardened Ramp	**MOD-6 Flushing Channel Closed**	• Downstream of hardened ramp, sediment deposited in wave like pattern. Scour still downstream of low flow channel. • Some sediment deposition on downstream-most portion of baffled section. Not all baffles utilized on ramp, however lower 1/3 still submerged.
	MOD-6 Flushing Channel Open	• Scour hole shifted to downstream of flushing channel. The rest of downstream sediment distribution uniform. • Like flushing channel closed configuration: some sediment deposition on downstream-most portion of baffled section. Not all baffles utilized on ramp, however lower 1/3 still submerged.

Table C-4. Model observations for MOD-9 design with flushing channel closed and open at 1,500 ft^3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-9 Flushing Channel Closed**	• More flow towards dam crest than in MOD-6, however, still did not activate crest.
	MOD-9 Flushing Channel Open	• No flow over dam crest.
Upstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• Flow split similar to MOD-6, however less pronounced with less sediment accumulation in front of gates 1-2. • Apron of hardened ramp almost fully covered by sediment.
	MOD-9 Flushing Channel Open	• Flow and sediment pulled toward the flushing channel inlet. Scour developed around the left wall of the hardened ramp. Some sediment removed from gates 3 and 4 of canal intake. No other sediment removed from apron
Upstream of Diversion Intake	**MOD-9 Flushing Channel Closed**	• Less sediment behind gates compared to MOD-6, however less uniform sediment distribution. • Flow favoring gates 1-2 with less sediment accumulation on gates 3-4.
	MOD-9 Flushing Channel Open	• Very little change observed
Downstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• Sediment deposition follows submergence pattern. Almost entire lower half of hardened ramp submerged with significant deposition in the low flow channel. Sediment deposition behind baffles not enough to bury baffles. • Downstream of hardened ramp follows similar deposition/scour patterns as previously seen.

Table C-5. Model observations for MOD-6 design with flushing channel closed and open at 3,000 ft^3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-6 Flushing Channel Closed**	• All banks fully submerged, and dam crest fully utilized. • Bed form still on left upstream side, ending in front of low flow channel of hardened ramp.
	MOD-6 Flushing Channel Open	• No significant changes to upstream river conditions from flushing channel closed configuration.
Upstream of Hardened Ramp	**MOD-6 Flushing Channel Closed**	• Some sediment accrued on gate 2 of hardened ramp, leading into the low flow channel. No sediment on gates 3-4, however the apron is covered by sediment. • Some scour off the bullnose, not visible with flow pattern, but seen on sediment after drained down. Large eddy off of flushing channel wall.
	MOD-6 Flushing Channel Open	• Apron exposed in front of flushing channel; flow split around channel wall caused turbulence at entrance, which enabled the flow to pull significant quantities of sediment. Apron in front of gate 3 up to part of gate 4 covered in sediment (except for portion eroded by bullnose). • Sediment accumulation seen in flushing channel closed configuration mostly removed from low flow channel section.
Upstream of Diversion Intake	**MOD-6 Flushing Channel Closed**	• Sediment highest in front of all gates of intake. This gradually slopes down into hardened ramp with lowest point in front of bullnose where scour occurred. • Sediment accrued in front of and partially up intake gates, however very little accumulated behind the gates in the intake.
	MOD-6 Flushing Channel Open	• Similar pattern observed as flushing closed where sediment highest in front of all gates of intake and gradually slopes down into hardened ramp with lowest point in front of bullnose where scour occurred. • Similar pattern to flushing closed with sediment in front of all gates except gate 4 exposed due to scour from flushing channel.
Downstream of Hardened Ramp	**MOD-6 Flushing Channel Closed**	• No significant sediment accumulation on the hardened ramp in the baffled section. However, ramp was still partially submerged for lower 1/3 with flow “dead zone”. • Scour hole downstream of low flow channel continued to deepen. The scour hole was the only area where sediment did not accumulate downstream.
	MOD-6 Flushing Channel Open	• Bottom 2 rows of baffles partially filled in with sediment, however tops of baffles still exposed and active. • Scour downstream of flushing channel combined with previously existing scour from low flow channel.

Table C-6. Model observations for MOD-9 design with flushing channel closed and open at 3,000 ft^3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-9 Flushing Channel Closed**	• Dam crest fully utilized. • Majority of sediment pulled towards hardened ramp as opposed to dam crest due to flow splits.
	MOD-9 Flushing Channel Open	• Dam crest fully utilized. • Majority of sediment pulled towards hardened ramp as opposed to dam crest due to flow splits.
Upstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• No sediment accrual on the hardened ramp. Apron in front of gates 1-2 also clear due to scour at left wall of hardened ramp. • Scour around bullnose on both sides, however, appears less than what was observed on MOD-6.
	MOD-9 Flushing Channel Open	• Same deposition pattern in/around hardened ramp as MOD-9 closed (above): next to no sediment accumulation on hardened ramp.
Upstream of Diversion Intake	**MOD-9 Flushing Channel Closed**	• Significant drop in sediment in front of intake gates. High point of bedform now in front of the low flow channel. • Portion of apron exposed at edge of apron and in front of gate 4 with less sediment on gates compared to MOD-6.
	MOD-9 Flushing Channel Open	• Flushing channel cleared out sediment accrual on gates 3-4 of intake. Still sediment on intake apron and gates 1-2. • Previous bed form where sediment in front of intake lower than in front of hardened ramp replaced with bedform in MOD-6 (intake entrance highest point of sediment sloping down towards bullnose).
Downstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• Baffles on edge of transition with low flow channel partially filled in with sediment, however still area for resting behind baffles • Scour downstream of low flow channel, the only area that did not have sediment deposition.
	MOD-9 Flushing Channel Open	• Baffles on edge of transition with low flow channel partially filled in with sediment, however still area for resting behind baffles • Significant scour downstream of flushing channel and hardened ramp.

Table C-7. Model observations for MOD-6 design with flushing channel closed and open at 6,000 ft^3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-6 Flushing Channel Closed**	• Riverbed set by leaving model running for 4 hours at 6,000 ft^3/s. Once bed form extends to hardened ramp, bed considered set. • All banks fully submerged, and dam crest fully utilized.
	MOD-6 Flushing Channel Open	• All banks fully submerged, and dam crest fully utilized. • Channel continued to shift left towards the flushing channel.
Upstream of Hardened Ramp	**MOD-6 Flushing Channel Closed**	• Sediment accumulated in front of canal to left side of bullnose. From right side of bullnose to left crest of dam, sediment is scoured. • Sediment in front of hardened ramp accrued on the apron in front of all gates with some sediment in front of low flow channel.
	MOD-6 Flushing Channel Open	• Sediment accumulated on low flow channel, though less than when flushing channel was closed. • Flushing channel was left open when flow was shut off, thus some sediment was left in the flushing channel after the model run.
Upstream of Diversion Intake	**MOD-6 Flushing Channel Closed**	• Sediment accrued in front of and partially up intake gates, however very little accumulated behind the gates in the intake. • Intake gates was the highest point of sediment accumulation with a steady downslope to the bullnose.
	MOD-6 Flushing Channel Open	• Sediment accrued in front of and partially up intake gates, however very little accumulated behind the gates in the intake. • Intake gates was the highest point of sediment accumulation with a steady downslope to the bullnose. Similar overall pattern to MOD-6 flushing channel closed with less accumulation on apron.
Downstream of Hardened Ramp	**MOD-6 Flushing Channel Closed**	• No significant sediment accumulation on the hardened ramp in the baffled section. However, ramp was still partially submerged for lower 1/3. • Scour hole downstream of low flow channel continued to deepen. The scour hole was the only area where sediment did not accumulate downstream.
	MOD-6 Flushing Channel Open	• No significant sediment accumulation on the hardened ramp in the baffled section. However, ramp was still partially submerged for lower 1/3. • Scour hole downstream of low flow channel extended to include downstream of flushing channel with ripple pattern of sediment accumulating to the right of scour hole.

Table C-8. Model observations for MOD-9 design with flushing channel closed and open at 6,000 ft^3/s.

Location	Configuration	Observations
Upstream River Conditions	**MOD-9 Flushing Channel Closed**	• Riverbed set by leaving model running for 4 hours at 6,000 ft^3/s. Once bed form extends to hardened ramp, bed considered set. • All banks fully submerged, and dam crest fully utilized.
	MOD-9 Flushing Channel Open	• All banks fully submerged, and dam crest fully utilized. • Channel continued to shift left, with sediment deposition mostly upstream of hardened ramp, less sediment accrued in front of dam crest and right bank.
Upstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• No sediment accumulation in front of flushing channel, some scour observed around bullnose. • No sediment accumulation on exit of low flow channel, very little sediment accumulated on apron of hardened ramp.
	MOD-9 Flushing Channel Open	• More sediment accumulation in the low flow channel, however confined to portion of gate 1. • Most sediment passed down hardened ramp and flushing channel without accumulating except in front of low flow channel where waves from flushing channel and bullnose overlapped and allowed sediment to drop on apron in front of gates 1-2.
Upstream of Diversion Intake	**MOD-9 Flushing Channel Closed**	• Sediment on intake gates 1-3, scour around flushing channel wall prevented accumulation in front of gate 4 with no sediment on apron in front of gate 4. • As seen in MOD-6 at the same flow rate, intake gates were the high point for sediment accumulation, with levels dropping until bullnose, where full scour was observed.
	MOD-9 Flushing Channel Open	• Similar sediment accumulation pattern as MOD-9 flushing closed gates 1-3 had sediment accumulation in front of and on gates. • As seen in MOD-6 and MOD-9 closed at the same flow rate, intake gates were the high point for sediment accumulation, with levels dropping until bullnose, where full scour was observed.
Downstream of Hardened Ramp	**MOD-9 Flushing Channel Closed**	• Some sediment deposition in transverse pattern observed, but not enough to fill in area behind baffles. • End-most portion of baffled area has flow “dead-zone” with large recirculating area.
	MOD-9 Flushing Channel Open	• Some sediment deposition in transverse pattern observed, but not enough to fill in area behind baffles. • End-most portion of baffled area has flow “dead-zone” with large recirculating area.