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Hydraulic Laboratory Report HL-2011-05

Physical Hydraulic Model Study of the Lower Yellowstone Diversion Dam Rock Ramp

Phase II
Lower Yellowstone Project
Montana Area Office


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

August 2011

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
July-2011	Technical	June 2010-March 2011

4. TITLE AND SUBTITLE
Physical Hydraulic Model Study of the Lower Yellowstone Diversion Dam Rock Ramp

Phase II
Lower Yellowstone Project
Montana Area Office

5a. CONTRACT NUMBER W59XQG91878418

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US. Department of Interior, Bureau of Reclamation
Hydraulic Investigations and Laboratory Services Group
PO Box 25007, Denver, CO 80225

8. PERFORMING ORGANIZATION REPORT NUMBER
HL-2011-05

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers, CENWO-PM-C
1616 Capitol Avenue
Omaha, Nebraska, 68102-4901

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Available from:
National Technical Information Service, Operations Division, 5285 Port Royal Road, Springfield, Virginia 22161
http://www.ntis.gov

13. SUPPLEMENTARY NOTES

14. ABSTRACT This study is the second of two phases of physical hydraulic modeling efforts related to the design of a new screened canal headworks, diversion weir and rock ramp fishway for endangered pallid sturgeon on the Lower Yellowstone River at Intake, MT. The diversion weir will provide adequate head for irrigation diversion flows through the new headworks structure. The rock ramp will span the full channel width and provide velocities and depths adequate for fish passage over the diversion weir. Phase 2 focuses on validation and optimization of the diversion weir and rock ramp through physical hydraulic modeling.

15. SUBJECT TERMS
Lower Yellowstone River Diversion Dam, MT, canal head works, diversion weir, diversion rating curve, rock ramp fishway, sturgeon passage, velocity and depth measurements, physical hydraulic modeling.

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Robert F. Einhellig
a. REPORT UL	**b. ABSTRACT** UL	**a. THIS PAGE** UL	SAR	113	**19b. TELEPHONE NUMBER** *(Include area code)* 303-445-2142

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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Mission Statements

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

Acknowledgments

This model study was funded by the Bureau of Reclamation's Montana Area Office and the Army Corps of Engineers. Thanks for the technical oversight and peer review that was provided by Kathy Frizell and Brent Mefford. Thanks to the Bureau of Reclamation's Laboratory Shops for their hard work in constructing the physical model.

Hydraulic Laboratory Reports

The Hydraulic Laboratory Report series is produced by the Bureau of Reclamation's Hydraulic Investigations and Laboratory Services Group (Mail Code 86-68460), PO Box 25007, Denver, Colorado 80225-0007. At the time of publication, this report was also made available online at **http://www.usbr.gov/pmts/hydraulics_lab/pubs/**

The funding for this project was provided by the USACOE under MIPR No. W59XQG91878418 from the Omaha District Office.

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Executive Summary

This section summarizes the report "Physical Hydraulic Model Study of the Lower Yellowstone Rock Ramp-Lower Yellowstone Project-Montana Area Office," HL-2011-05, U.S. Department of Interior, Bureau of Reclamation, Denver, CO, March 2011.

Hydraulic modeling results are provided for the diversion weir and rock ramp designs proposed for the Lower Yellowstone Project. The modeling investigated flow conditions for a 1,600 ft long ramp of increasing slope, three levels of ramp choking, a 1300 ft long steepened toe version of the ramp, and the use of surface boulder fields to locally alter ramp flow conditions. Primary data were gathered for 7,000, 15,000, 30,000, 40,000 and 70,000 ft^3/s. The results include:

- The laterally sloping dam crest and downstream ramp provide adequate diversion head to provide for irrigation diversions at river flows above 3,000 ft^3/s. Figure 20 (pg 25) shows the rating curve for the upstream headworks and weir crest recorded in the model. These measurements validate the assumptions used in the numerical modeling effort by the COE using HEC-RAS.

- Depth and water surface elevation measurements (pgs 27 – 31) confirmed that choking the ramp with fines at post construction and natural choking due to sediment movement will not affect upstream diversion. Velocity measurements made for varying levels of ramp "choking" indicated that choke material reduced interstitial flow within the rock matrix. Velocities near the weir crest were reduced by the choke material but were still greater than 6 ft/s for critical passage flows. Downstream, velocities increased in critical passage areas due to reduced roughness which narrowed passage corridors with acceptable flow conditions (pgs 33 – 37).

- A boulder field was found to improve passage areas near the crest by reducing velocities and increasing depth near the right bank. At 30,000 ft^3/s the boulder field reduced crest velocities to less than 6 ft/s in a section approximately 150 ft wide next to the right bank (Figure 41). In this same section depths were always greater than 3.5 ft (Figure 42). Recommendations for implementing a boulder field in the rock ramp are provided.

Passage corridors over the ramp were not negatively impacted by the shortened version (C2) of the ramp. Velocity data that resulted from the shortened ramp (pgs 48 – 59) show that tailwater inundation of much of the steepened ramp surface resulted in little change for fish passage. Depth and velocity results showed that the shortened ramp can be used without compromising acceptable flow conditions in critical passage corridors.

Background

Reclamation’s Lower Yellowstone Project in east-central Montana and western North Dakota includes the Lower Yellowstone Diversion Dam, Thomas Point Pumping Plant, the Main Canal, 225 miles of laterals, and 118 miles of drains. The purpose of the project is to provide a sustainable water supply for irrigation to land along the west bank of the Yellowstone River.

The diversion dam was constructed between 1905 and 1909 on the Yellowstone River about 18 miles downstream of Glendive, Montana, near the small town of Intake, MT. It is a rock-filled timber crib with a structural height of approximately 12 ft and a maximum hydraulic height of about 5 ft as the diversion.   Figure 1 shows the dam in 1910 as originally constructed with the head works on the far bank.

Figure 1. Lower Yellowstone Diversion Dam shortly after completion in 1920.

The dam has been damaged by large ice flows many times over the years. Damage is typically repaired by dumping rock on the dam crest using an overhead cableway. Every few years the irrigation district adds more rock to the dam to recover the upstream water surface elevation required to divert water into the Main Canal.   The hydraulic drop across the structure combined with turbulent flow conditions on the dam prevent upstream passage of pallid sturgeon, a listed species. In addition, the canal entrance is not screened, allowing all life stages of fish to be entrained into the canal. Figure 2 shows a recent view of flow over the dam crest. Dumped rock across the dam crest forms a highly irregular crest with turbulent flow extending well downstream.

Figure 2. Lower Yellowstone Diversion Dam today with large rock dumped along the dam crest that has migrated downstream over the years preventing fish passage.

Introduction

Intake Dam is a Bureau of Reclamation irrigation diversion dam on the Yellowstone River approximately 70 miles upstream from its confluence with the Missouri River. It presents a barrier to sturgeon migration up the Yellowstone River. The proposed project consists of constructing a screened headworks structure to prevent fish (including the federally protected pallid sturgeon) from entering the irrigation diversion canal, a new diversion weir, and a gradual slope rock ramp across the entire dam face to provide suitable flow conditions for upstream pallid migration, figure 3 (a plan and section of the proposed design). The proposed new weir crest ran the entire width of the river with a 70 ft wide thalweg section at elevation 1988.1 ft located in line with the existing river thalweg. The crest then gently sloped with a few breaks up to the banks on both sides of the river. The rock ramp sloped downstream with four sections of slopes 0.2%, 0.4%, 0.6%, and 0.8% respectively (Figure 4). A previous 1:20 physical hydraulic model evaluated the screened headworks structure, preliminary design of the new weir, and bed load sediment movement.

This study provides a detailed evaluation of flow conditions on the diversion weir and downstream rock ramp using a 1:25 scale physical hydraulic model. The model was used to investigate the dam crest head discharge rating, ramp geometry and roughness, fish passage corridors defined by flow velocity and depth, and flow conditions at the ramp toe. The U.S. Army Corps of Engineers (COE) conducted one and two-dimensional numerical hydraulic modeling of the river, ramp geometry, and Intake diversion in conjunction with this study (USCOE 2010b).

Objectives

The primary objectives of the rock ramp model study are:

- Develop a head vs. river discharge rating for the diversion dam and ramp structure.
- Evaluate rock ramp and dam crest flow conditions (average velocity and depth).
- Provide hydraulic data to support design of the facility with respect to rock ramp roughness, stability, and scour issues.
- Evaluate ramp flow conditions and revise design geometry to enhance fish passage. This would include the potential addition of fish passage opportunities in the form of boulder fields, depressions, thalweg improvements, etc.
- Evaluate hydraulic conditions for a shorter ramp with a steepened toe.

Physical Hydraulic Model Description

A 1:25 (model/prototype) Froude Scale model of the proposed Intake diversion dam and rock ramp located on the Lower Yellowstone River near Glendive, Montana was constructed by Reclamation's Hydraulic Investigations and Laboratory Services Group in Denver, Colorado. The model included a block out of the screened headworks under construction and the existing headworks, the proposed diversion weir and the entire rock ramp fishway.

Model Scaling

The model scale was chosen to provide the best opportunity to measure depth and velocities on the ramp crest while fitting the model into the laboratory space. The model was specifically designed to investigate hydraulic conditions; therefore, Froude scaling was used for the model. Froude law similitude provides the following relationships for the 1:25 scale model:

Length and depth ratio: $L_r = 25:1$

Velocity ratio: $L_r^{1/2} = 25^{1/2} = 5:1$

Discharge ratio: $L_r^{5/2} = 25^{5/2} = 3,125:1$

The Hydraulic Model

The 1:25 Froude scale model of the diversion weir and rock ramp was constructed in the same model box as the previous Intake Diversion Dam headworks model. The model, however, was lengthened to attain space for including the full rock ramp and sufficient downstream river channel for evaluating scour development at the ramp toe. Figure 3 shows the outline of the proposed ramp design from the COE numerical modeling with the model box outline overlaid onto an aerial photo of the existing diversion facility.

Figure 3. Extent of the 1:25 scale model of the diversion weir and rock ramp

The model included approximately 2,300 ft of the river and rock ramp with 500 ft upstream of the diversion weir, 1,600 ft rock ramp and 300 ft downstream of the ramp. The 1600 ft long rock ramp is herein referred to as the Concept 1 (C1) design. The upstream length provided optimum approach conditions to the weir crest and minimized the influence of laboratory support columns within the rock ramp and slope. Slopes were maintained in the model by placing vertical plywood templates at slope break-lines specified in the ramp design (blue lines in Figure 4). The relative roughness of the rock ramp was modeled using geometrically scaled angular rock which was placed to grade using the plywood break-lines. A rock gradation was provided by the COE (D_{100} = 3 ft) that was used in the majority of the ramp. A larger gradation of rock was used for the thalweg section (D_{100} = 4 ft). A detailed discussion of the rock gradations and roughness is provided in the Testing Procedure section.

Exterior structures of both the new and existing headworks were included in the model as they will remain in the river near the new diversion weir. Neither headworks structure was operational in the model. The proposed 10 ft wide diversion weir crest was constructed of Perma-Ply sheeting with a 2:1 concrete slope transitioning upstream to the fixed river topography. Construction photos are shown in Appendix D.

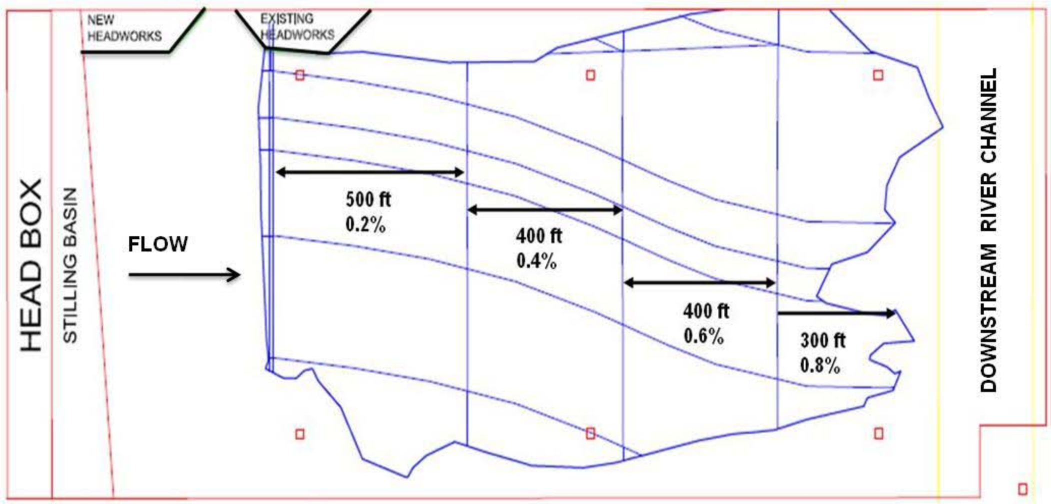


Figure 4. Schematic of the C1 rock ramp design in the physical model.

Flow discharged out the end of the model about 300 ft downstream from the proposed intersection of the ramp with the existing thalweg as shown in Figure 5. For this phase of the study the gradation of the river bed material downstream of the ramp was not modeled; therefore, scour at the ramp toe was not investigated. It was anticipated that the slope on the lower third of the ramp and the tie–in with the existing river channel would be modified to investigate shortened ramp options as a second phase of the study. The existing diversion dam and downstream river channel were not modeled as part of the investigation.

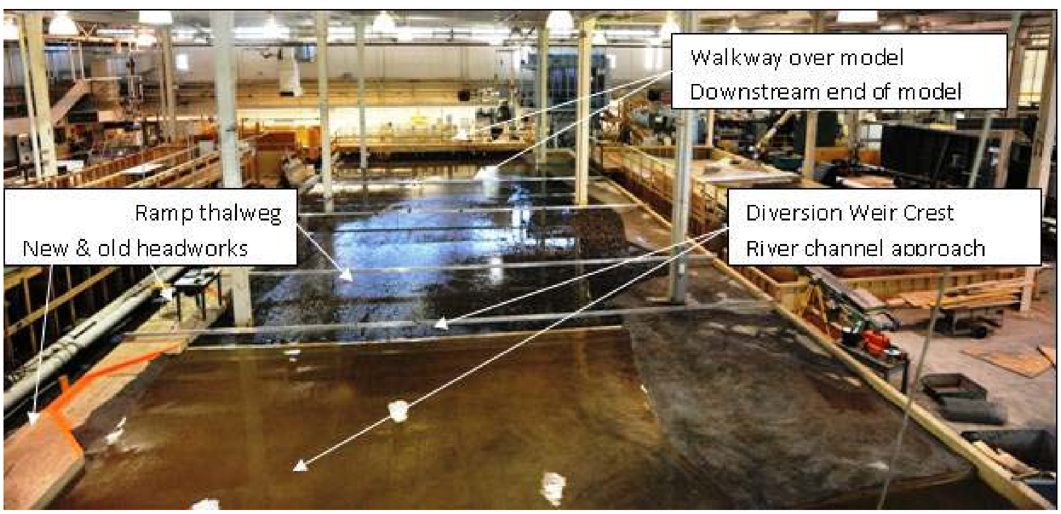


Figure 5. Overall view of hydraulic model looking downstream consisting of the new headworks structure, approaching river channel, diversion weir, and rock ramp.

Instrumentation

Flow Measurement

A 250,000-gallon storage reservoir located under the laboratory floor supplied water for the hydraulic model through an automated flow delivery and measurement system. Water was delivered to the model using two 100-150 hp variable-speed permanent laboratory pumps and two temporary 40-60 hp auxiliary pumps located next to the model. A combination of these pumps provided the necessary flow rates for each flow scenario tested.

Model flow ranged from 3 to 17 cubic feet per second (ft^3/s or cfs). Flow from permanent laboratory pumps was measured using calibrated Venturi meters. Three Venturi sizes (6, 8, and 12 inch diameter) were used according to the amount of flow through the pipe. A 44,000 pound volumetric/weigh tank facility is used to calibrate the laboratory Venturi meters at regular intervals to an accuracy of $\pm 0.25\%$. Flow from the auxiliary pumps ranged from 1.8 to 7ft ^{3}/s and was measured using a Controlotron ultrasonic pipe flow meter on a 10 inch PVC pipe (accurate to ± 2.0%).

Water Surface Elevations

Water surface elevations were measured with either piezometer taps or MassaSonic M-5000 Smart Ultrasonic Sensors. The MassaSonic units measure from 4 to 40 inches with an accuracy of ± 0.25 percent of maximum distance or 0.1 inches (0.0083 ft) at 40 inches and a resolution of 0.01 inches. A sample rate of 100 Hz was used with the software displaying the average of 32 samples. Taking into account error that comes from the sensor, survey instrumentation, and human error an uncertainty analysis showed that the uncertainty for water surface measurements is ± 0.218 ft prototype. All elevation, depth, velocity, and flow data in this report are listed in prototype units unless otherwise specified.

Water surface elevations measured upstream of the dam were taken using piezometer taps located in the thalweg as shown in Figure 6. Taps 1-4 were located 423, 373, 271, and 179 ft upstream of the weir crest respectively.

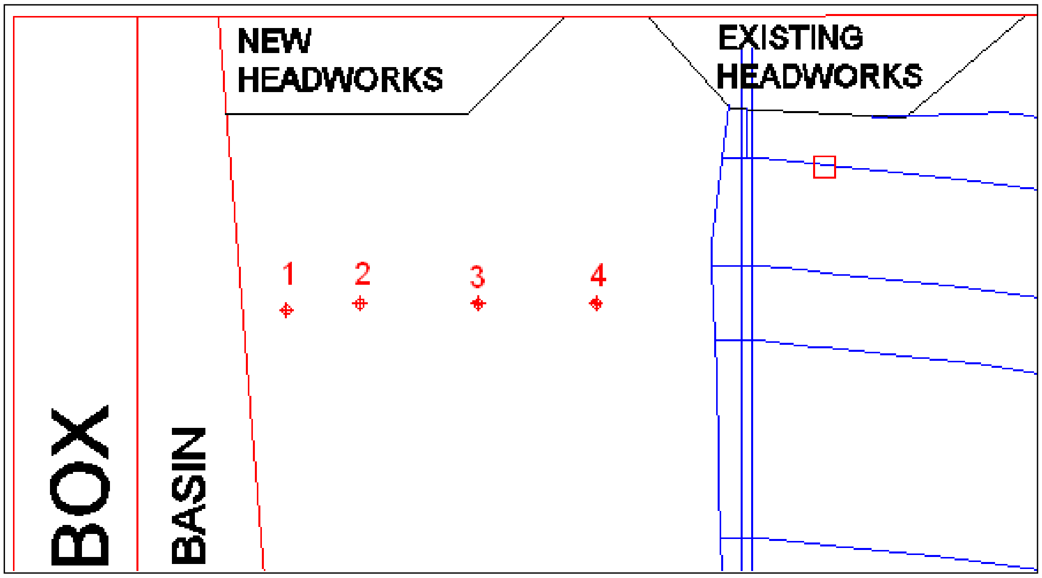


Figure 6. Location of upstream water surface elevation piezometer taps.

Tap 1 measurements represent the diversion headwater elevation due to its location relative to the new headworks. It was connected to a stilling well with a down-looking MassaSonic sensor as well as a separate stilling well with a Vernier point gauge for verification (Figure 7a). The point gauge could be read to the nearest 0.001 ft in the model (0.025 prototype ft).

Tailwater elevation downstream of the ramp was measured using a piezometer connected to a stilling well equipped with a level sensor, similar to the headwater measurements (Figure 7b). The tap was located 1,653 ft downstream of the weir crest. Prototype tailwater levels at the location of the tap were determined from a HEC-RAS numerical river model run by the COE for each simulated river flow, see Section 4 in Figure 8. Model tailwater elevation was set by inserting or removing picket boards at the exit of the model until the target setting was obtained in the stilling well.

The COE provided water surface data for the prototype based on numerical simulations using both ADH 2D (Adaptive Hydraulics Modeling) and HEC-RAS (1D River Analysis System). HEC-RAS modeling produced lower water surface elevations resulting in lower flow depths and higher velocities over the ramp. The HEC-RAS model was chosen to set the tailwater in the physical model as it provided more conservative values for evaluating fish passage performance.

(a) (b)

Figure 7. Stilling well and MassaSonic sensors to measure headwater water surface elevation (a) and tailwater water surface elevation (b).

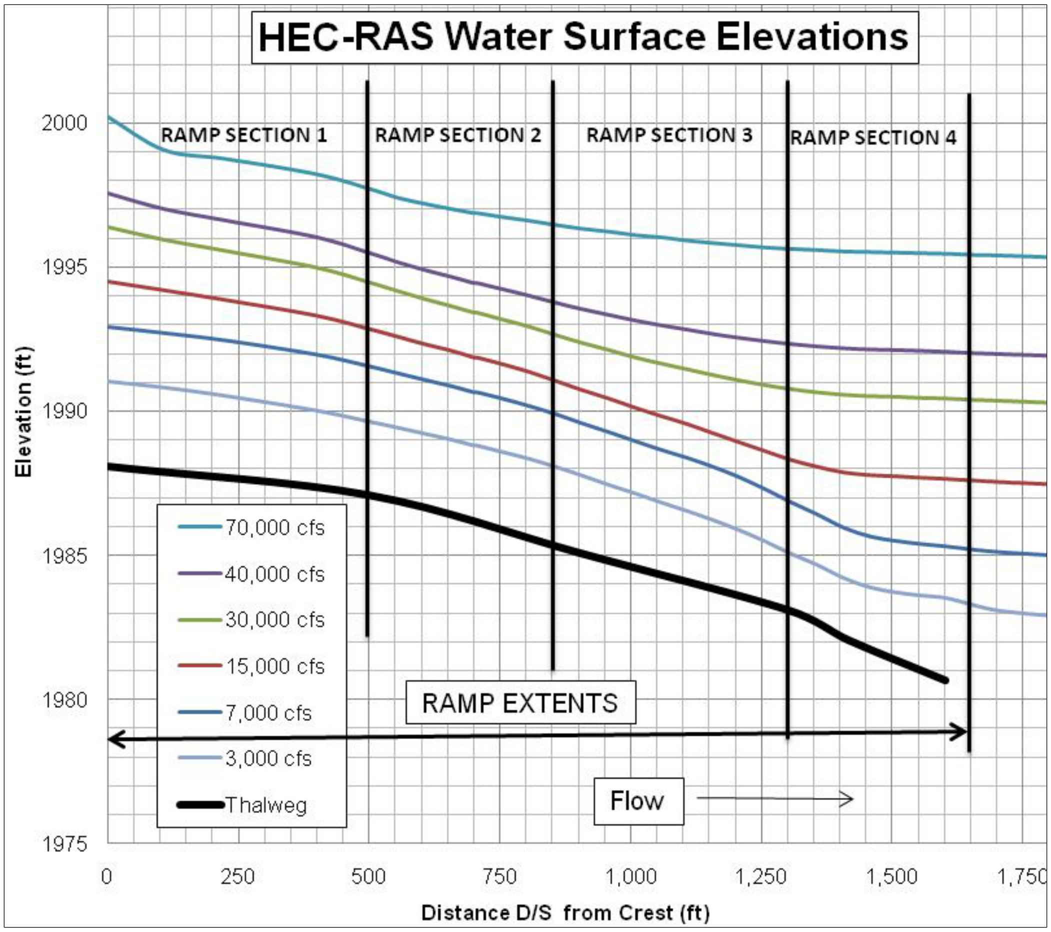


Figure 8. Water surface elevations for the C1 ramp developed from COE HEC-RAS modeling.

Approach Flow Settings

The approach flow was set by utilizing the flow from three pipes that feed the model head box upstream of a rock baffle. An upstream flow boundary was established in the model 100 ft upstream of the dam crest, (Figure 9). Velocity data were measured at 50 ft intervals across the flow boundary and compared to ADH model velocity results. The horizontal flow distribution entering the physical model was adjusted to closely match numerical model predictions by altering the distribution of flow between the three inlet pipes and adding sections of fine mesh screen downstream of the rock baffle in areas where velocities exceeded numerical model predictions. The supply pipe closest to the river thalweg was utilized first, providing as much flow as possible directly into the river channel then the other two pipes to the right were added as the flow increased. This worked well. Only the area near the right bank exceeded target velocities requiring supplemental baffling with screens. Specific screen baffling configurations were determined for each flow condition except for 3,000, 7,000, and 15,000 ft^3/s which did not require screens. Table 1 shows tailwater, pump, and approach screen settings used for each flow scenario. Ramp flow presented in Table 1 accounts for the river flow minus 1,374 ft^3/s diversion flow and flow bypassing the diversion and ramp through an upstream high flow flood channel that conveys flow above 30,000 ft^3/s river flow.

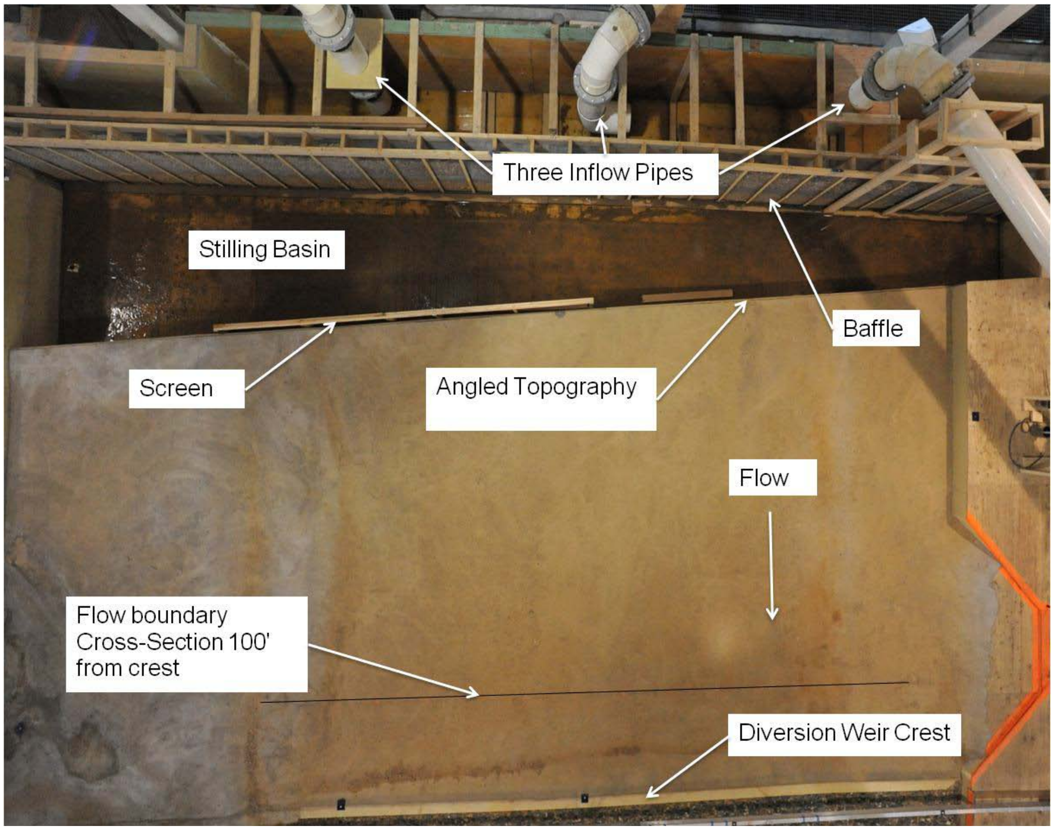


Figure 9. Features used at the inflow of the physical model for accurate simulation of flow conditions approaching the weir crest and rock ramp.

Table 1 – Settings used in physical model for correct simulation of approach flow conditions.

Upstream Flow	**Ramp Flow**		**Tailwater W.S. Elevation**	**Pumps**	**Approach Screens**
-	Prototype	Model	D/S Stilling Well		
cfs	*cfs*	*cfs*	*ft*	-	-
3,000	1,600	0.51	1983.29	1 auxiliary	No Screen
7,000	5,626	1.80	1985.20	1 auxiliary	No Screen
15,000	13,626	4.36	1987.62	1 auxiliary	No Screen
30,000	27,646	8.85	1990.38	2 auxiliary + NW	Big screen, sq screen at mark (10' 1 3/8" from Headworks)
40,000	36,676	11.74	1992.02	2 auxiliary + NW	Big screen only
70,000	63,176	20.22	1995.42	2 auxiliary + NW+NE	Big screen, sq screen on right side, sq screen on right end overlapping big screen

Velocity Measurements

Velocity data were collected with Nixon 403 Streamflo Velocity meters and a handheld SonTek 2D FlowTracker Acoustic Doppler Velocimeter (ADV) shown in Figure 10. Nixon meters were mounted to aluminum channels that spanned across the model and collected velocity data at 60% of the flow depth. They were used for their ability to measure velocities in depths as low as about 15 mm (0.60 model inches) where other instrumentation wouldn't work. A spinning rotor in the water sends a frequency through the probe and to the Streamflo indicator unit. A calibration for each Nixon probe relates the frequency to a velocity. These meters operate in the range of 0.16 to 4.92 ft/s (0.8 – 24.6 prototype ft/s) and have an accuracy of ± 2.0%.

The SonTek FlowTracker ADV, mounted on a 6 ft wading rod, was used to collect velocity data upstream of the weir crest for approach conditions as well as in-between channels and downstream of the ramp. The FlowTracker is a side-looking instrument with a 10 cm (3.94 inch) sample distance. The instrument measures two-dimensional velocity vectors in a small remote sampling volume (about 0.1 in^3) by emitting sound pulses (pings) at a specific frequency that reflect off of particles in the water. The FlowTracker has a sample rate of 1 Hz and an accuracy of ± 1.0% of the measured velocity. It operates within a range of 0.003 to 13.0 ft/s (.015 – 65 prototype ft/s).

(a) (b)

Figure 10. Nixon Streamflo Velocity meter (a) and a SonTek 2D FlowTracker (ADV) mounted on a 6 ft wading rod (b) used to measure local velocities in the physical model.

Data Acquisition

Measurements made with MassaSonic sensors and Nixon meters were recorded with a data acquisition system while data from the manometer board, point gauge, and FlowTracker were recorded individually. MassaSonic sensors and Nixon meters were placed next to each other, one on each of the four aluminum channels where they could collect depth and velocity data at the same location as shown in Figure 11. Data from these four locations on the rock ramp was recorded simultaneously with the sensors at the headwater and tailwater locations.

Water surface elevation, flow depth, and velocity data were collected simultaneously using an IOtech Personal Daq/3000 Series data acquisition unit. This unit collected voltage data from each sensor and meter that were connected through cables that ran along the channels. The voltage data was then transferred to a Lap Top computer with version 9 of Data Acquisition System Laboratory (DasyLab). Within this program the data was manipulated using coefficients and calibrations specific to each instrument to display and record prototype scale data. The data was then imported into a spreadsheet where they were formatted for analysis and presentation.

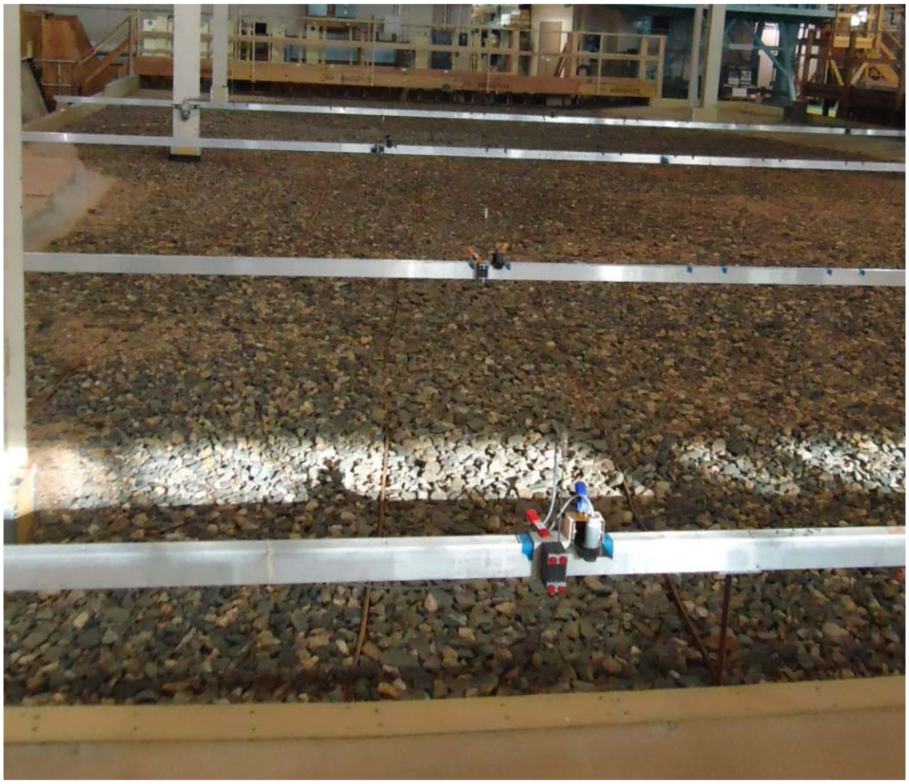
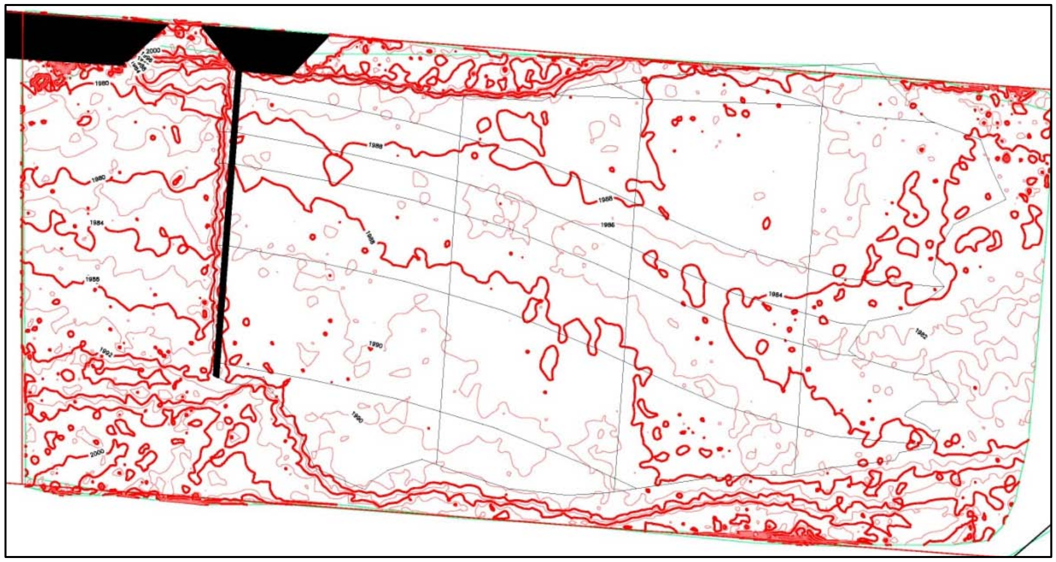


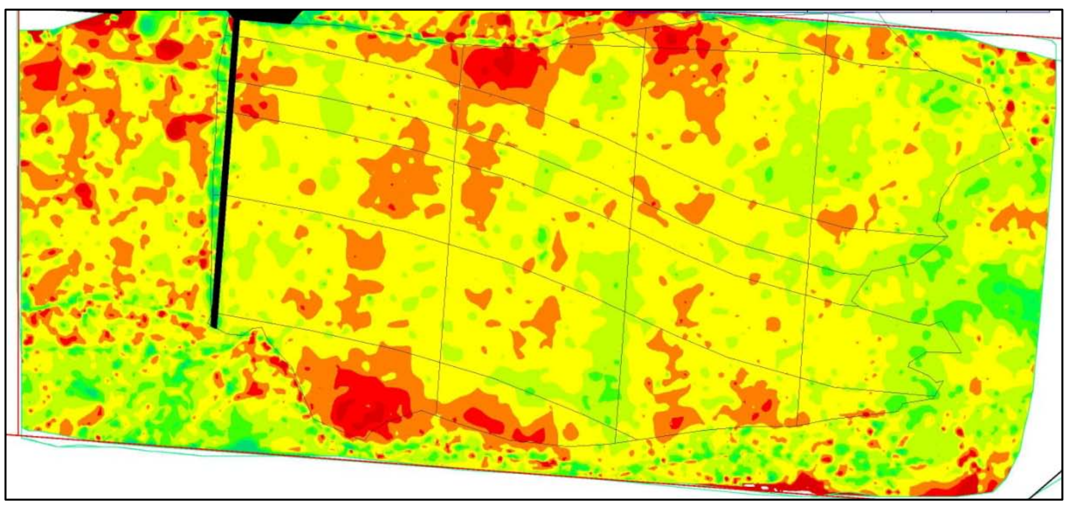
Figure 11. MassaSonic sensors placed next to Nixon meters to record depth and velocity simultaneously at the same location.

Photogrammetry

High quality photographs processed with near field photogrammetry software were used to show changes to the ramp as it was modified with choke material, boulder fields, and toe changes as well as monitor model elevation tolerance of the rock ramp. A Nikon D700 digital camera was mounted on a cable 22 ft above the model ramp. Several overhead photos were taken covering the model. These photos were processed to produce a digital elevation model (DEM) using reference points captured in the photographs. The DEM was then imported into AutoCAD Civil 3D where elevation contours were created for the physical model (Figure 12a). The map in Figure 12 (b) shows that most of the ramp was within ± 1 ft of the specified elevation as defined in Table 2. One foot scales to just under one half inch model which is about one-half the diameter of the rock used in the model. Using the photogrammetry technique on the irregular rock surface gives an average surface elevation of about one half the mean rock diameter below the top of rock, closely matching the design surface elevation.



(a)



(b)

Figure 12. Model elevation contours (a) and differences between as-built model and design elevations (b) from photogrammetry.

Table 2. Elevation differences corresponding to Figure 12 physical model elevations.

Elevations Table				
Number	Minimum Elevation	Maximum Elevation	Area	Color
1	−16.75	−3.00	78936.73	
2	−3.00	−2.00	252130.44	
3	−2.00	−1.00	842934.25	
4	−1.00	0.00	795081.70	
5	0.00	1.00	245713.44	
6	1.00	2.00	50046.24	
7	2.00	3.00	14911.78	
8	3.00	19.01	28585.49	

Investigations and Testing Procedure

Initial Model Testing

Initial model testing was performed to calibrate model flow settings and verify the correct operation of flow control equipment and testing instrumentation used on the model. Testing included setting correct approach flow conditions upstream of the ramp as well as setting downstream tailwater levels for each flow scenario. All flow settings upstream and downstream of the ramp were made based upon 2-D numerical modeling conducted by the COE.

Diversion Head Evaluation

First, the diversion weir and C1 ramp design was tested to verify that the diversion structure met design requirements for upstream pool elevation. Water surface elevations at five locations upstream and at the weir crest were measured and compared to 2-D numerical results of the upstream rating curve. This was done for each flow scenario with particular interest in the lower flows (3,000 and 7,000 ft^3/s).

Diversion pool elevation is also dependent on the relative roughness of the rock ramp. Due to floods and sediment deposition over the ramp, it is expected that the roughness of the ramp will change over time, most likely decreasing. To assure that irrigation diversions can be met in the future, water surface measurements were made under different roughness conditions described in the Choking the Ramp section of this report.

Figure 13 shows the locations signified by red dots where measurements were made to verify the upstream water surface elevation for diversion. Green dots show locations where velocity and depth data were measured on the ramp. Data was collected in the thalweg at each of the four measurement cross sections (locations 6, 13, 19, and 25) and all the way across the ramp at the 1st and 3rd cross sections (locations 5-11 and 18-23). Results from these cross-sections were also used to analyze the three levels of choking the ramp described in the next section.

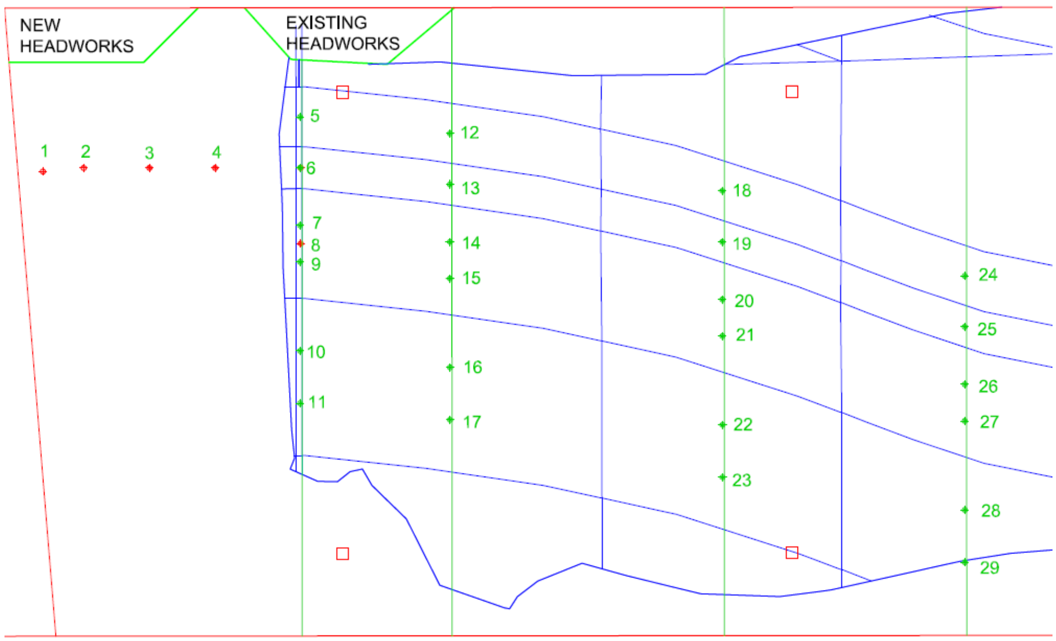


Figure 13. Test locations for diversion and ramp roughness measurements. Red dots are piezometer tap locations, green lines are aluminum channels for instrumentation and green dots are depth and velocity locations.

Ramp Choking

Choking the ramp refers to adding cobble to sand sized material to the ramp surface. Choke material is added to reduce post construction interstitial flow through the rock matrix which also reduces surface roughness and increases riprap stability when the ramp is constructed using large rock. Three levels of ramp choking were tested using the locations shown in Figure 13 to understand how upstream diversion and hydraulic conditions on the ramp are affected. The first test was of riprap material only (No-Choke condition), the second was choke material washed in to about ½ the rock diameter (Mid-Choke condition), and third test was of choke material washed into the riprap until only about 3 to 6 inches prototype of rock was exposed (Full-Choke condition). The thalweg was not choked to the Full-Choke level as higher velocities in the prototype will likely wash choke material out, leaving much of the riprap exposed in this area.

Comparison of results from these tests served as a sensitivity analysis of ramp hydraulics to choking to assure that diversion and fish passage goals will continually be met as the ramp changes over time.

Depth and velocity results were compared to results from the COE's ADH numerical model to help bracket the prototype roughness. The numerical model used two roughness values (Manning's n = 0.032 and 0.043) which were determined from standard recommendations given by Chow (1959) and (USCOE, 2010a). Manning's n values were determined from physical model results by applying the same theoretical calculations to the thalweg section of the ramp.

Choking material applied to a riprap surface is designed similar to the reverse of a gravel filter placed beneath riprap. A gravel filter beneath riprap is designed to prevent migration of the base material through the filter and then migration of the filter through the riprap on top. The following are typical guidelines for design of gravel filters (Reclamation, 1987):

$D_{50}(\text{filter}) / D_{50}(\text{base}) < 40$

$5 < D_{15}(\text{filter}) / D_{15}(\text{base}) < 40$

$D_{15}(\text{filter}) / D_{85}(\text{base}) < 5$

In the case of choking the rock ramp, the rock ramp material is considered the filter and the choke material considered the base. The concept of "choking" rock ramps has successfully been tested (Mefford, 2009). He found that when applied to rock ramps with coefficients of uniformity (C_u) of 1.60 and 1.32, the subsurface or interstitial flow was greatly reduced. Surface flow increased with greater penetration of choke material into the coarser rock, resulting in reduced ramp roughness. Guidelines specific to choke material were developed as:

$D_{50}(\text{Ramp Material}) / D_{50}(\text{Choke Material}) < 40$

$100 < D_{15}(\text{Ramp Material}) / D_{15}(\text{Choke Material}) < 200$

$D_{15}(\text{Ramp Material}) / D_{85}(\text{Choke Material}) < 5$

For the Yellowstone Intake model ramp, a 3/8" breeze material with fines was used as the choke material. The choke guidelines were met with values of 31.5, 162.5, and 4.33, respectively. C_u values of the rock gradations used were approximately 1.50 and 1.39 for the smaller and larger rock. The gradations for both rock sizes and the choking material are shown in Figure 14.

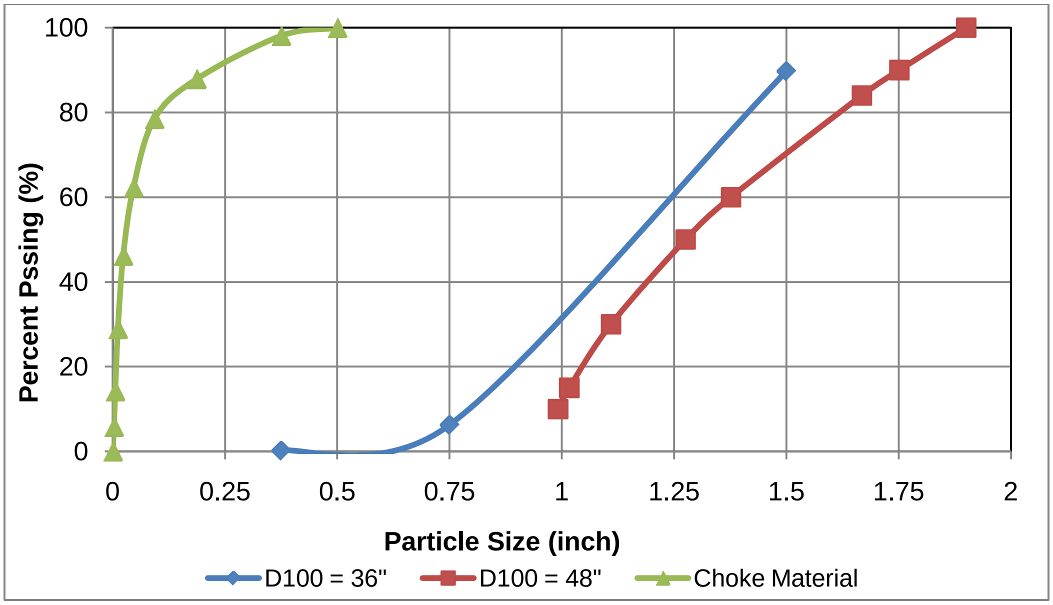


Figure 14. Gradations of the rock and choking material used in construction of the model rock ramp.

The choking material was washed into the rock using hoses. Figure 15 shows a sample area of the application of the choke material before and after it was washed into the rock.

Figure 15. Photo showing the rock ramp with washed choke material in the bottom left corner and the choking layer prior to washing into the rock in the top right corner.

Passage Optimization

Fish Passage Criteria

Biological Review Team (BRT) recommendations for depth and velocity for passage of adult pallid sturgeon are as follows:

- Flow depth should be generally greater than 1 m during the normal migration period, with ½ m minimum for all areas considered passable.
- Passage velocities are less than 6 ft/s for adults with 4 ft/s preferred, and less than 1-2 ft/s for juveniles (Jordan, 2009).

The passage criteria are based on observed flow preferences of adult pallid sturgeon in the Missouri and Lower Yellowstone Rivers, (Bramblett, 1996) laboratory swim studies of shovelnose sturgeon (used as a surrogate species for pallid) (White & Mefford, 2002), and juvenile pallid swim studies (Kynard, 2002) and (Adams, 1999). Additional insight on swim performance on rock ramps was drawn from monitoring data for other sturgeon species passing similar style structures (Vogel, 2008). Experience with pallid sturgeon movement over rough substrates or through velocities above 4 to 6 ft/s is very limited. The uncertainty of passage preference and swim ability required that the rock ramp design provide a range of flow conditions between passage corridors allowing individuals to select preferred passage routs as they negotiate the ramp. Interim data from the study were presented to the BRT for review and comment during the study. Comments were incorporated into the design and testing of the ramp.

Additional Features for Passage Optimization

This phase of testing focused on potential features to be added or changed on the ramp that would likely enhance fish passage without any significant changes to the ramp geometry. Boulder fields and shallow bottom depressions have been studied and used on other rock ramps to improve passage.

These features add complexity to the flow field generally aimed at increasing fish holding areas and decreasing average flow velocity. Previous ramp designs using boulder fields (Mefford, 2005) have successfully enhanced fish passage (Reclamation, 1998). For Intake, a boulder field design using large boulders (5 to 6 ft diameter) buried about ½ the boulder diameter below the ramp surface was evaluated in the model. Boulders were placed about 3 to 5 diameters apart to the right of the ramp thalweg as shown in Figure 16. Boulder fields decrease velocities and increase depths in strategic areas of the ramp by providing additional roughness due to drag forces caused by the boulders. Boulders are a potential benefit to passage as they provide roughness in desired locations that is less likely to change over time. Boulder fields create a passage way with decreased flow without spanning the entire ramp width, providing various paths the fish may choose to swim up the ramp. Turbulence caused by the boulders as well as stability during ice flows may be drawbacks to this feature.

Incorporating shallow scooped-out depressions were also considered as a means to increase fish holding areas on the ramp. Depressions that formed on the GCID (Glen Colusa Irrigation District) rock ramp constructed on the Sacramento River provided resting areas for green sturgeon but also may have been the cause of slower migration rates (Vogel, 2008). It is still not known if these pools are an aid or a hindrance to upstream migration. Depressions were not tested in the Intake physical model due to the difficulty in acquiring accurate test results at the model scale.

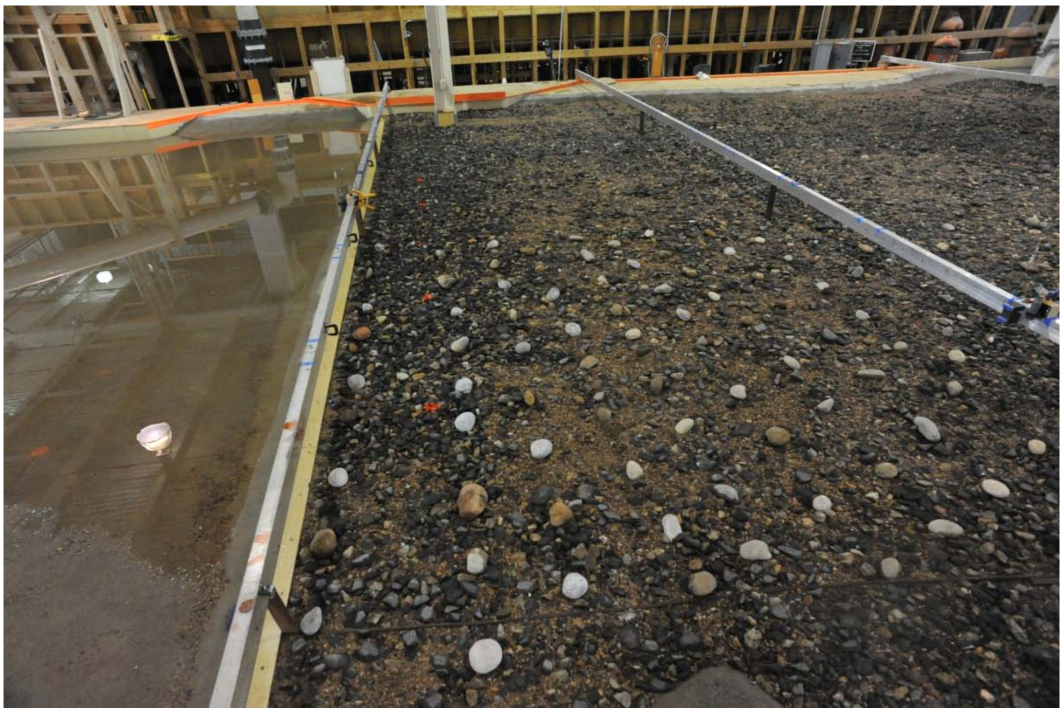


Figure 16. Example of a boulder field tested on the model rock ramp.

Boulder fields were tested as a means of decreasing flow velocities in critical passage areas on the ramp determined by previous results from roughness testing. Testing included depth and velocity measurements at common locations on the ramp with various boulder fields. Testing with no boulders on the ramp was first completed to obtain a baseline. Several iterations of boulder fields with various widths and boulder spacing were made before a preferred design was selected. All testing was done at 30,000 ft^3/s representing peak conditions for fish migration. The final configuration was tested at other flow rates.

For passage optimization, test locations were re-labeled from those used for roughness testing (Figure 13) to be more intuitive as to their position on the ramp. Figure 17 defines the re-labeled test locations along with additional locations on the crest near the right bank and on the downstream slope break lines at 500 and 900 ft downstream of the crest. In addition to localized data points, flow visualization techniques were used on the final two boulder fields. Flow visualization, which included inserting dye and confetti into the flow, enhanced understanding of how the flow is influenced by the boulders and average velocities through the entire boulder field were approximated.

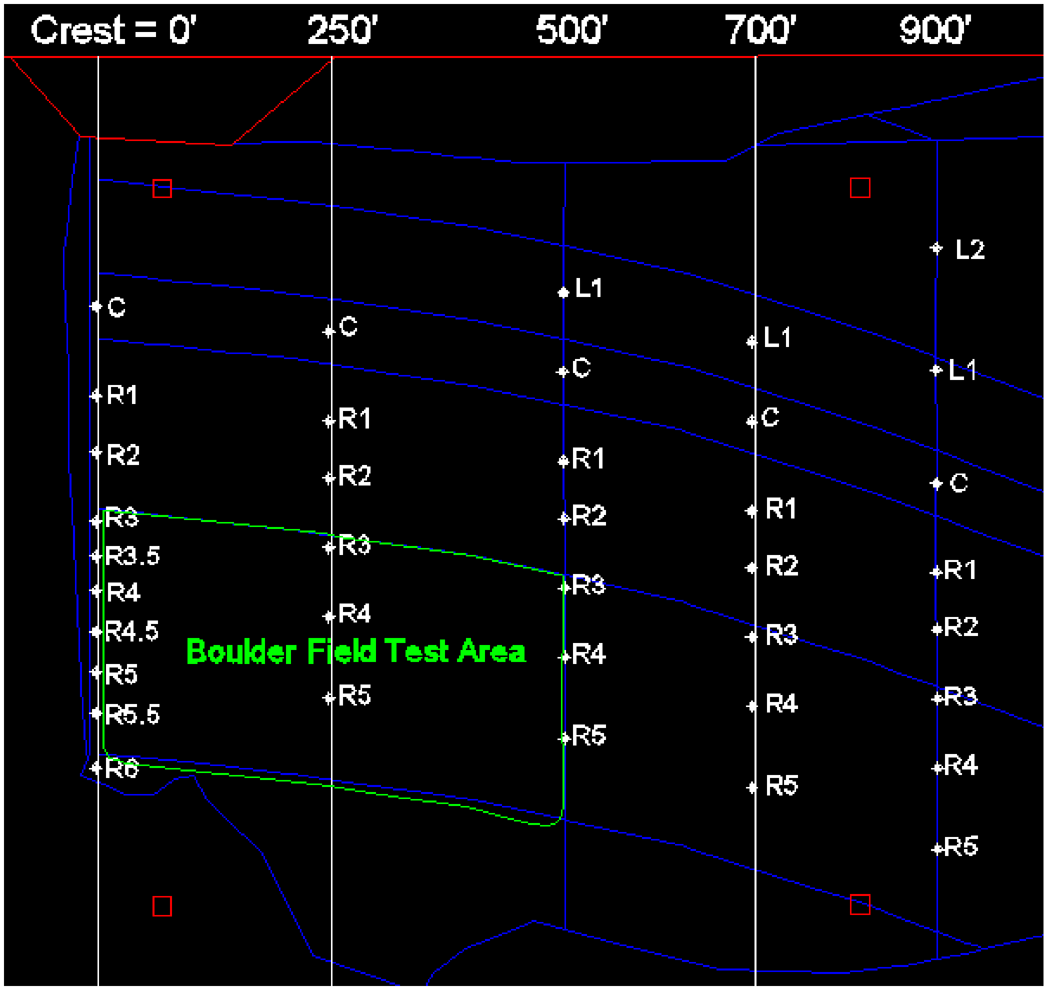


Figure 17. Test locations and area for boulder testing for passage optimization.

Ramp Concept 2 (C2) - 1300 ft Long Ramp with Steepened Toe

In an effort to reduce the ramp size and cost, COE requested that a shorter version of the rock ramp with steeper slopes near the downstream toe be investigated. The modification was made to the physical model which included doubling the slope on the left side to about 1.2% and a 2% slope near the right bank as shown in Figure 18, where the bold outline indicates areas that were steepened from the C1 ramp. The C2 ramp reduced overall surface area by approximately 21 percent.

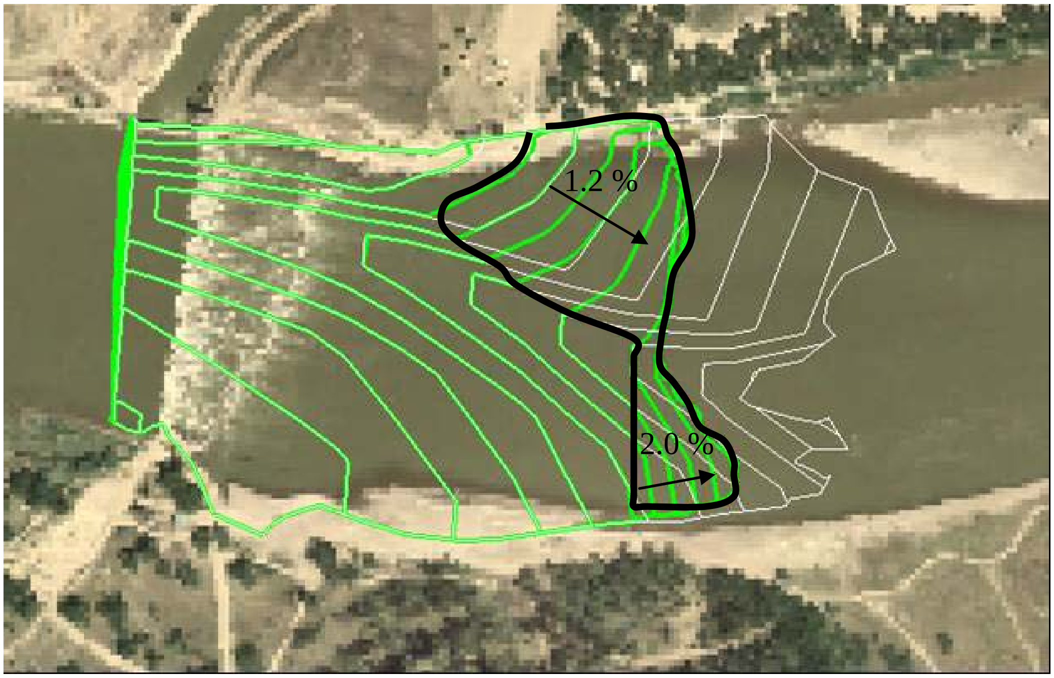
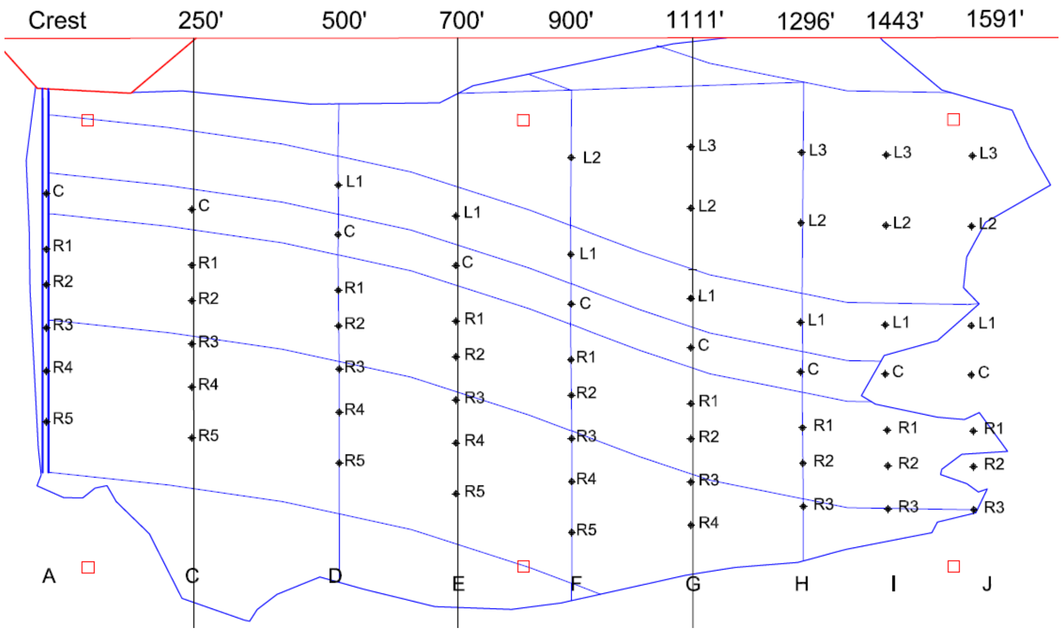
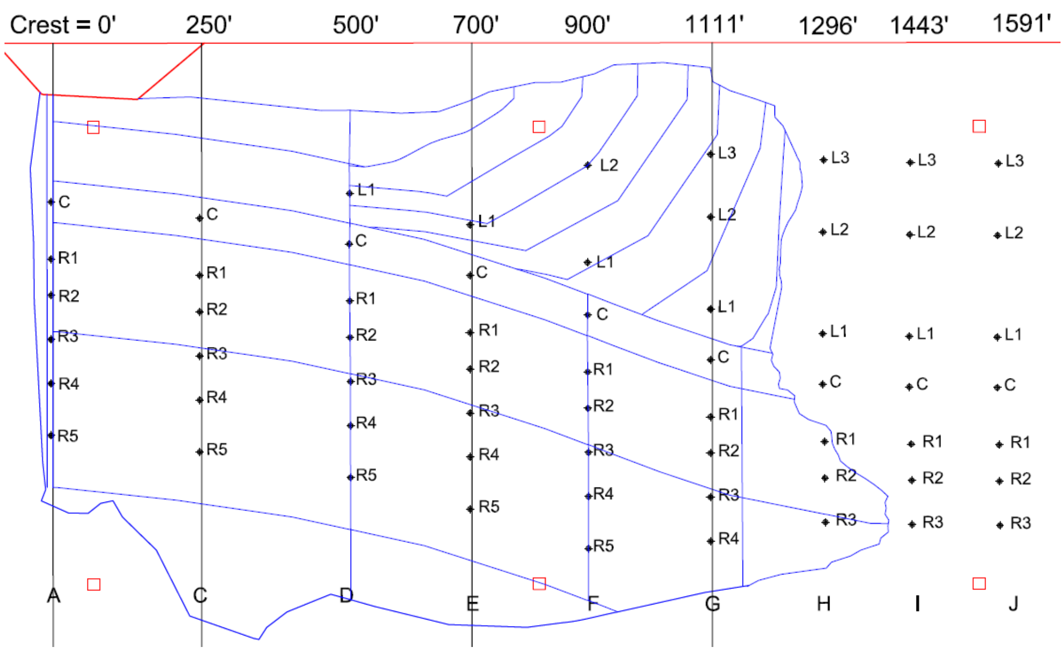


Figure 18. Plan view of shortened ramp geometry (green) compared to the longer version (white).

Fish passage and energy dissipation were concerns with a shorter ramp. These concerns were addressed by comparing data from C1 and C2 ramp designs at test locations shown in Figure 19. Results from the physical model were also compared to results from an ADH numerical model produced by the COE. Knowing where the tailwater begins to influence flow coming down the ramp was critical in determining potential ramp length. Water surface elevations at 700 and 1,111 ft downstream of the weir were helpful in finding the point of intersection with the tailwater for each flow scenario. Velocity data on and downstream of the ramp were necessary to address fish passage and energy dissipation concerns as well as detect tailwater influence.



(a)



(b)

Figure 19. Test locations used in investigating the C1 (a) and C2 (b) rock ramps.

Results and Discussion

Diversion Weir Rating

Comparisons of water surface elevations measured in the physical model to target rating curves are shown in Figure 20. Rating curves for the new canal headworks and weir crest were established from COE's HEC-RAS modeling simulations and field surveys conducted by the U.S. Geological Survey. Water surface elevations measured in the model near the new diversion headworks closely matched the design rating curve. Physical model results also closely matched the design rating at the weir crest with about 0.4 ft difference noted at 30,000 ft^3/s where a break-in-slope is indicated in the 2008 USGS water surface survey data.

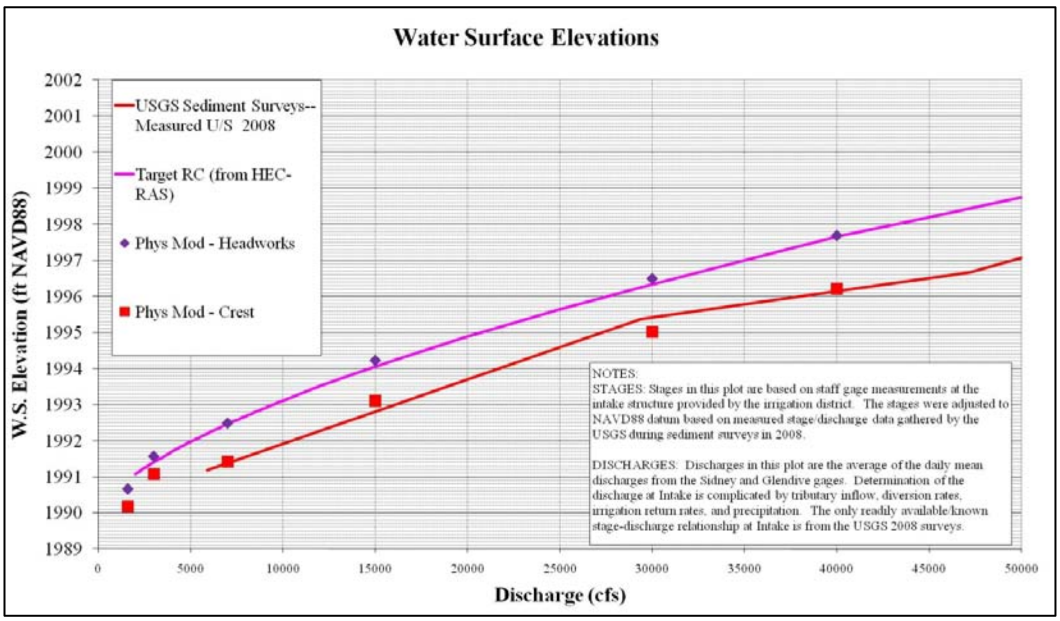


Figure 20. Comparison of water surface elevations measured in physical model to rating curves for new headworks and diversion weir.

Results from the physical model showed that there was no significant change in the upstream rating curve with ramp roughness.

Flow Conditions for Diversion Weir and C1 Rock Ramp – Physical vs. Numerical Results

Water surface elevations, depths, and velocities results from the physical model are compared to numerical results in figures 21 through 25. Numerical results shown in these figures were generated by the COE using the ADH 2D model with Manning's n values of 0.032 and 0.043. The ADH simulations showed water surface elevations that were about 1 foot greater on average than the rating curve derived using the HEC-RAS model. Data from the physical model shown here were taken in the thalweg of the ramp before any choke material was applied. Comparisons of physical and numerical data at other choke conditions are in Appendix A. Water surface elevations from the physical model were generally lower than simulation results for both numerical models. This was especially the case at the first break in slope, 250 ft downstream of the weir crest (distance "0" indicates location of crest in figures with flow going left to right). Physical model water surface elevations most closely compared to numerical model results for a Manning's "n" value of 0.032 with increased similarity with increased river flow.

Velocity results from the physical model showed an opposite trend from the numerical results. While numerical velocities increased down the ramp, velocities in the physical model were significantly higher on the weir crest and then decreased with distance down the ramp and were slightly less than the numerical results. Flow over the majority of the ramp surface followed this trend which was also apparent for 30,000 and 40,000 ft^3/s (Figures 23 and 24).

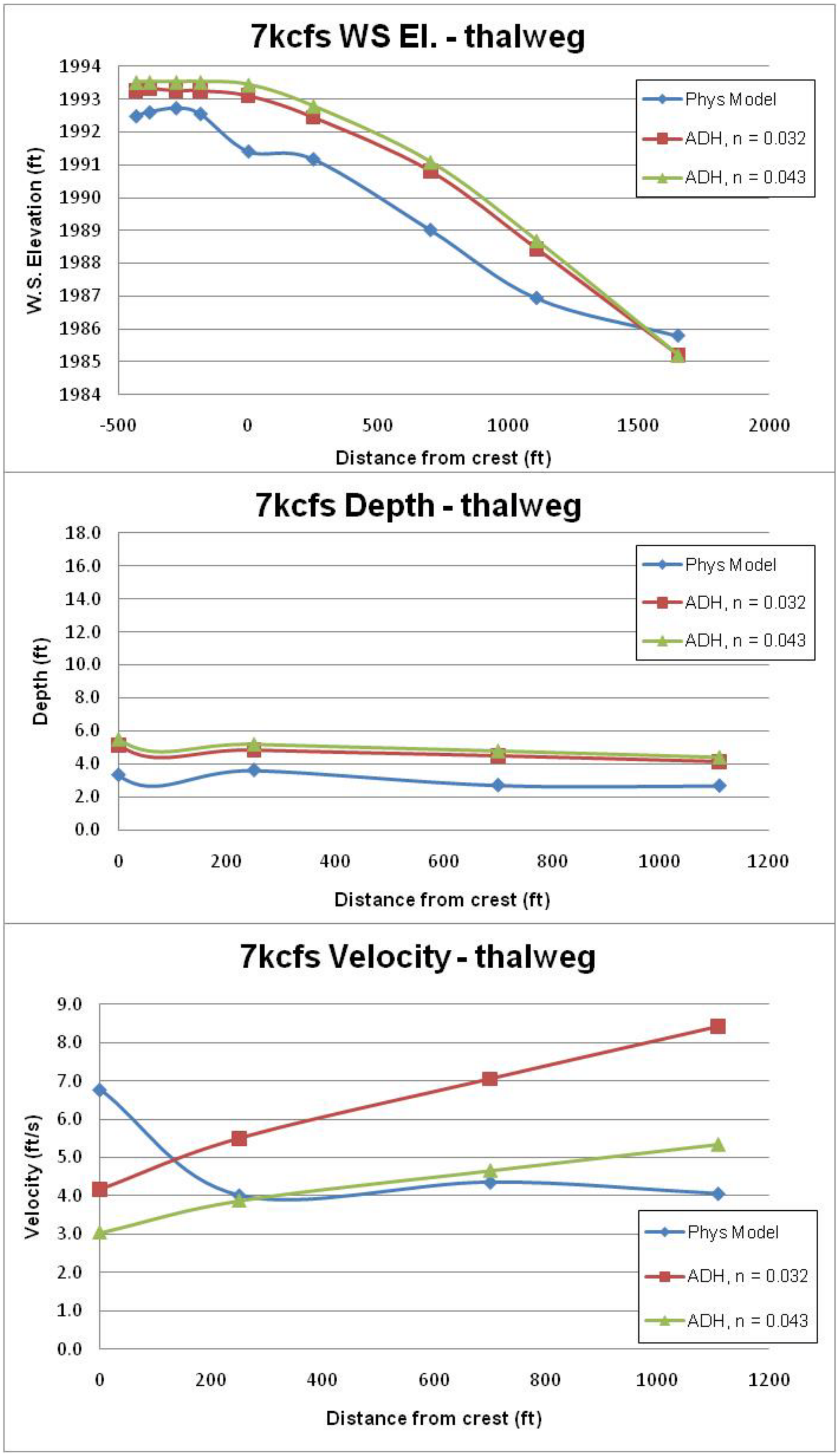


Figure 21. Water surface elevation, depth, and velocity results from physical and ADH numerical model over the rock ramp for 7,000 ft^3/s.

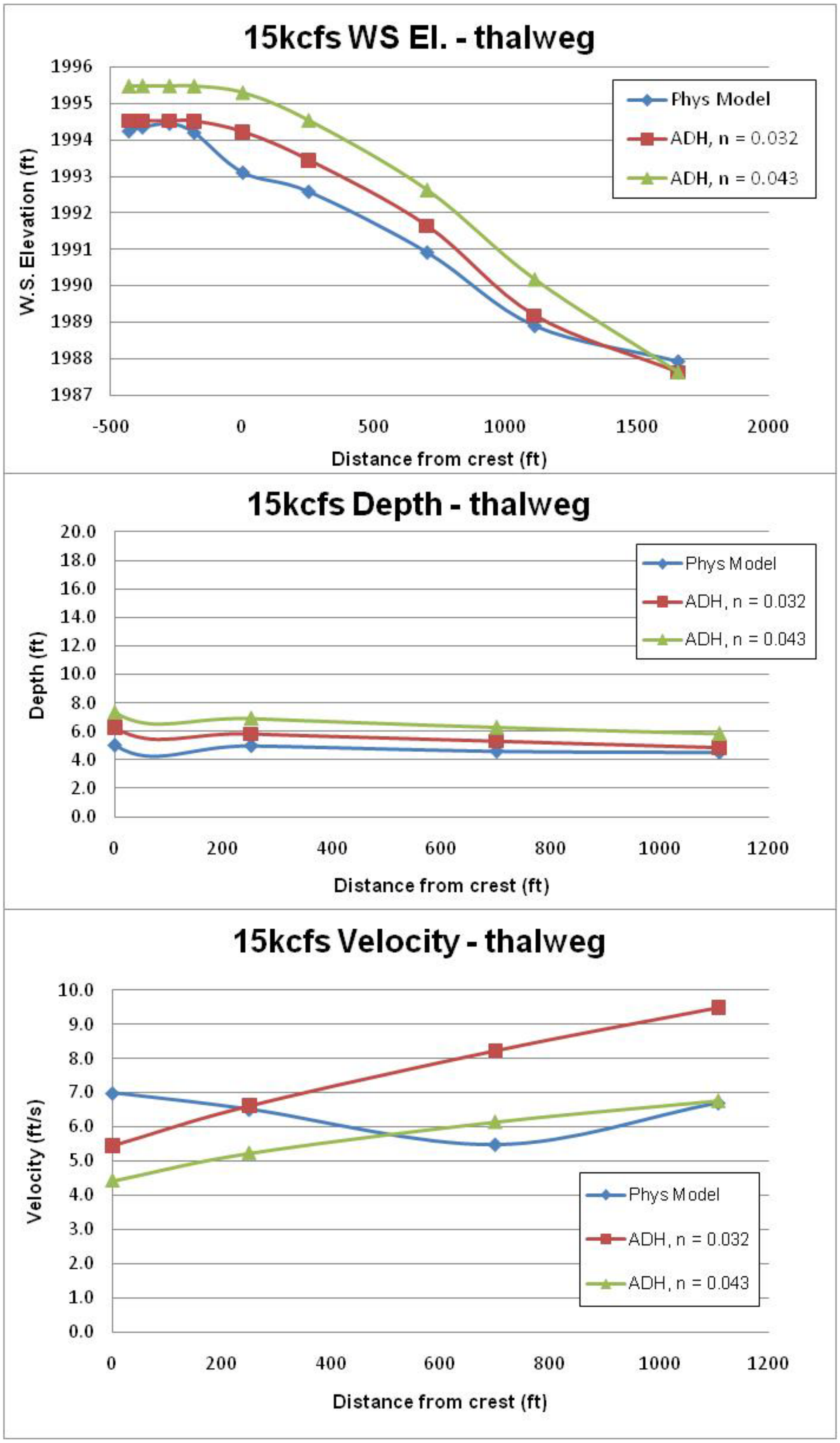


Figure 22. Water surface elevation, depth, and velocity results from physical and ADH numerical model over the rock ramp for 15,000 ft^3/s.

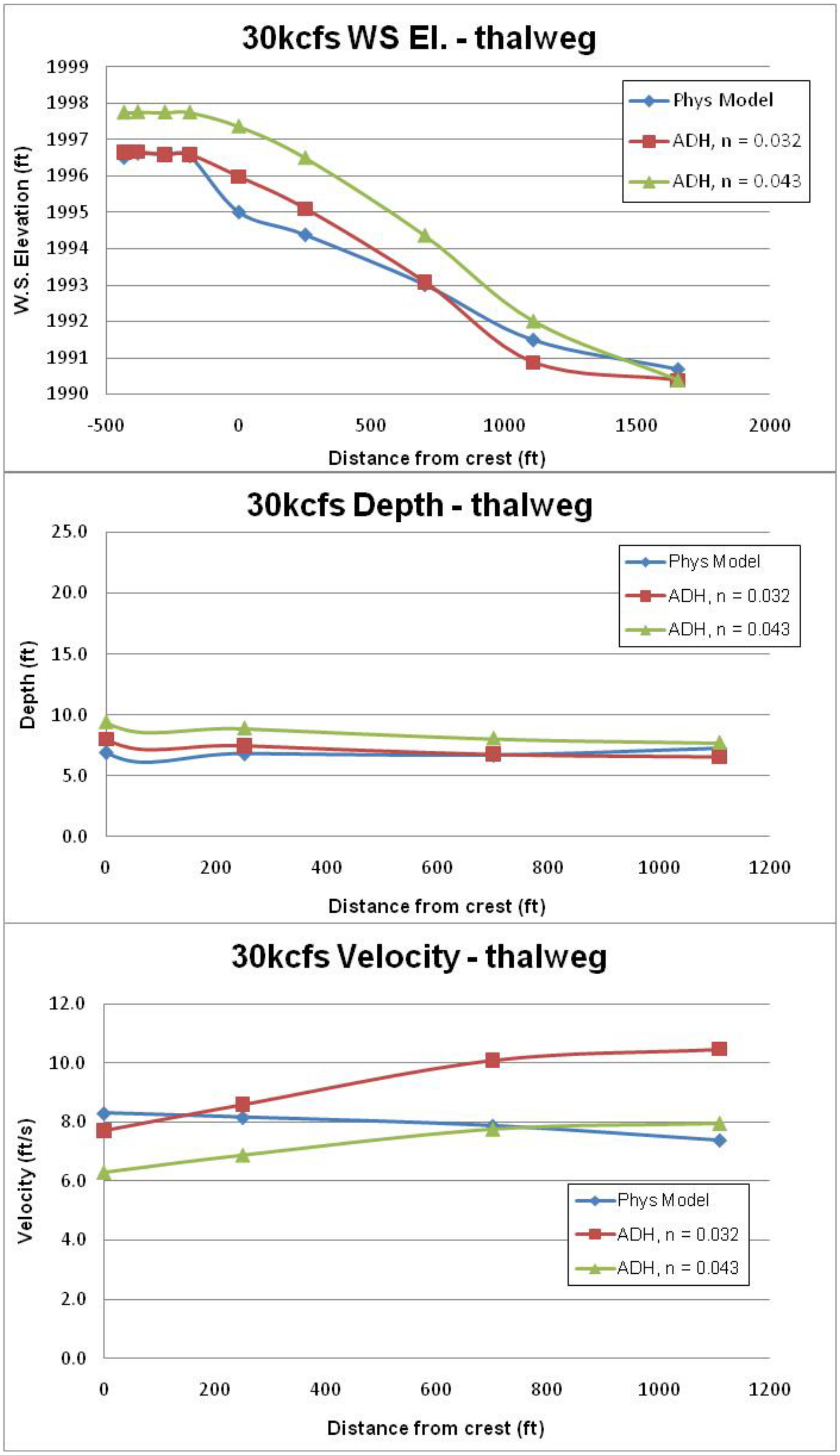


Figure 23. Water surface elevation, depth, and velocity results from physical and ADH numerical model over the rock ramp for 30,000 ft^3/s.

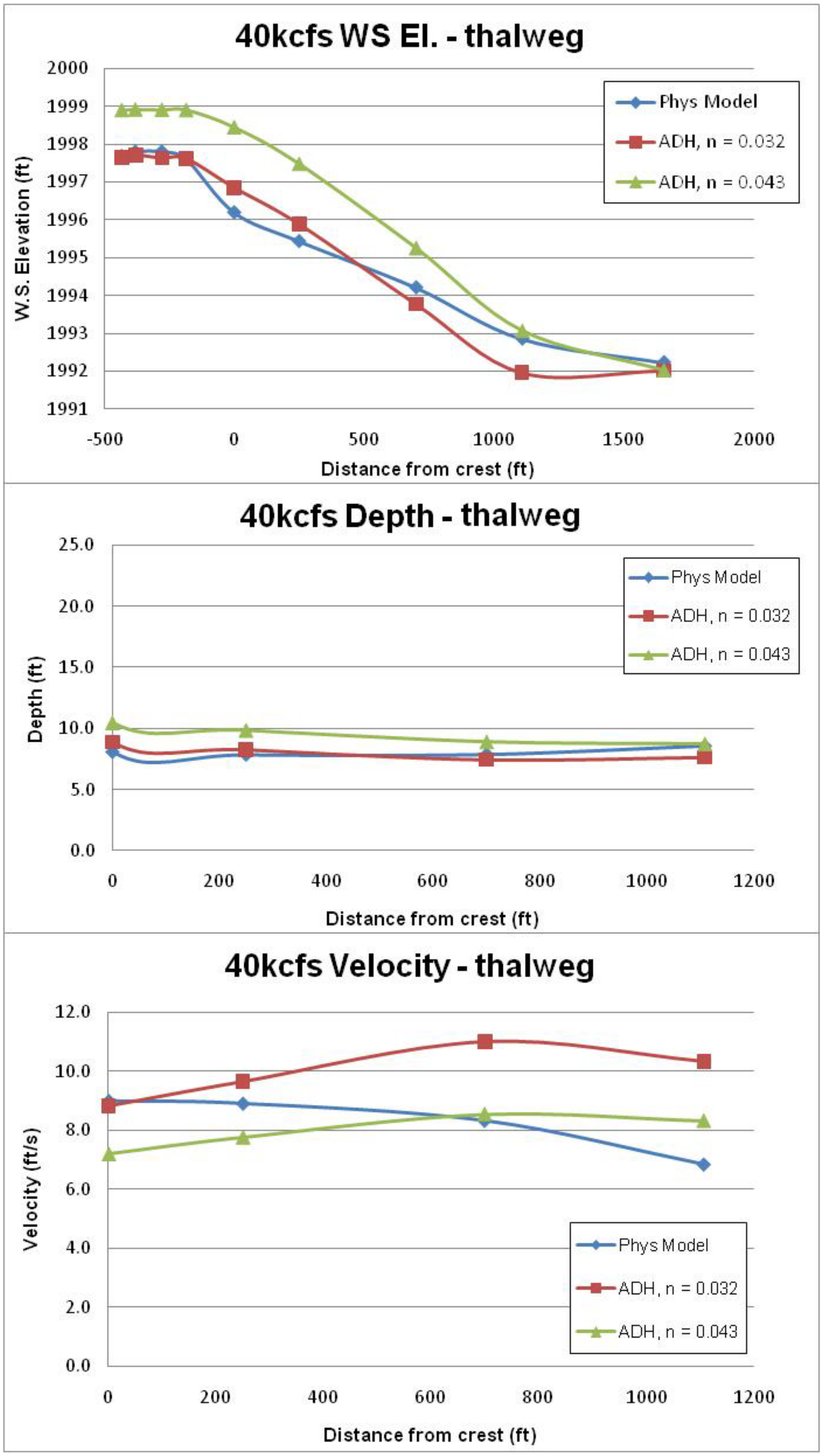


Figure 24. Water surface elevation, depth, and velocity results from physical and ADH numerical model over the rock ramp for 40,000 ft^3/s.

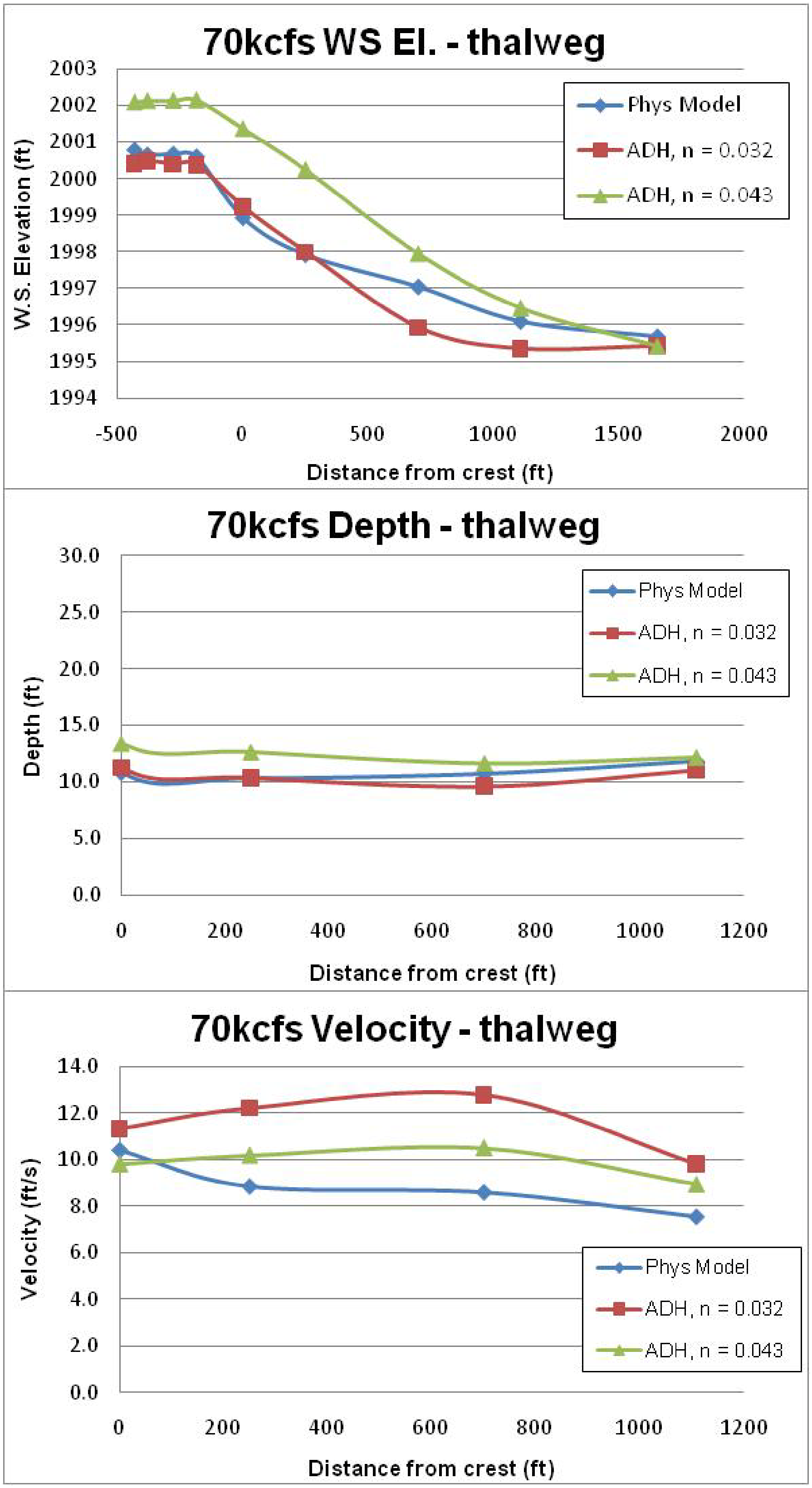


Figure 25. Water surface elevation, depth, and velocity results from physical and ADH numerical model over the rock ramp for 70,000 ft^3/s.

Water surfaces in the physical model at the weir crest were consistently lower and velocities higher than predicted by the ADH model. Figure 26 shows velocities across the entire crest length for 30,000 ft^3/s as an example. A noticeable acceleration of flow over the crest was observed in the physical model (Figure 27).

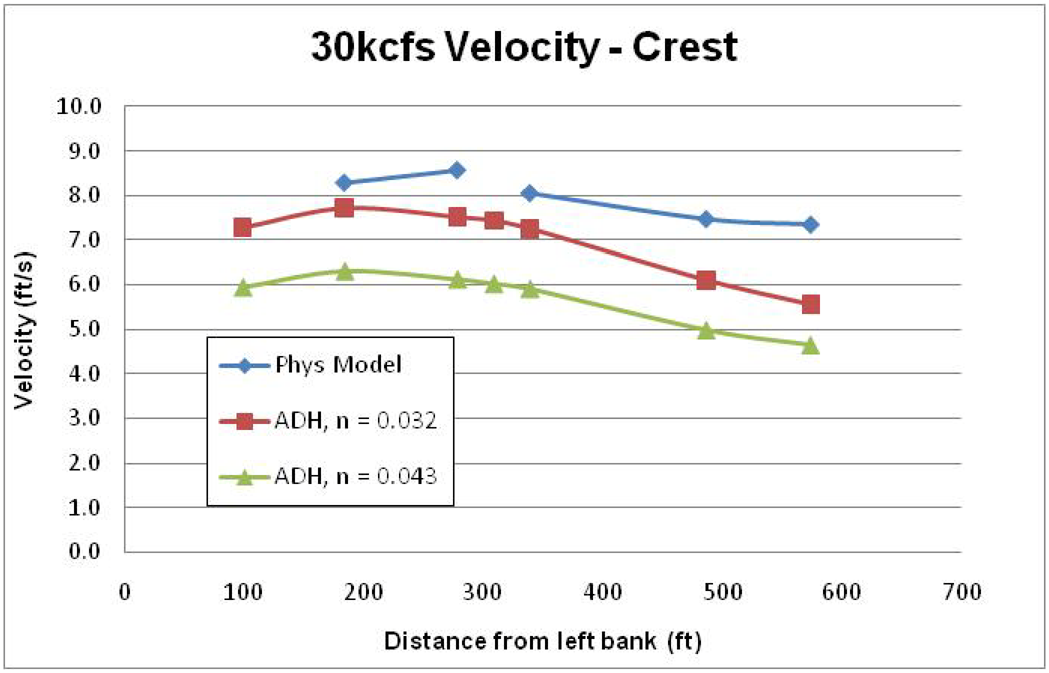


Figure 26. Comparison of physical and numerical velocity results across the weir crest, looking downstream.

Figure 27. Photograph showing the flow contraction and acceleration over the weir crest.

Diversion Weir and C1 Rock Ramp Discussion

The differences in physical and numerical results for depth and velocity at the weir crest and on the upstream areas of the ramp may be due to several factors. The most significant factor at lower river flows is how well the models simulated the loss of surface flow to interstitial flow on the ramp. The numerical model simulations assumed no loss of surface flow to interstitial flow on the ramp. It is also unclear how well the 2D model simulates the local near field effects of vertical acceleration at the crest. For lower river flows this likely overestimated the flow depth underestimated velocities.

The physical model, although representing interstitial flow may have overestimated interstitial flow in some areas of the ramp as the riprap layer thickness in the model was likely thicker than the prototype design would require. Despite differences in physical and numerical results, the physical and HEC-RAS models confirm that the upstream water surface elevation required to provide full diversion to the canal can be met. These models gave somewhat lower upstream water surface levels than the ADH model.

Choking the Ramp

Three levels of choking were tested in the physical model as shown in Figure 28. The entire ramp surface was choked with the exception of a full-choke in the thalweg (Figure 28, c), due to greater velocities that will be likely in this area. Depth and velocity data were collected at various locations on the weir crest and rock ramp. Comparing results showed how changes in interstitial flow and relative surface roughness of the ramp influenced hydraulic conditions which may impact fish passage over the structure.

(a) (b) (c)

Figure 28. Photographs of rock ramp at the no-choke (a), mid-choke (b), and full-coke conditions (c) that were tested in the model.

Ramp Choking Results

Test results in Figures 29 through 34 show how depths and velocities were affected by choking the C1 ramp. Results in these figures are presented in cross-sections at the weir crest and on the ramp 700 ft downstream of the crest looking downstream. Data collected at 15,000, 30,000, and 40,000 ft^3/s are presented as these flows are the most critical to passage of adult pallid sturgeon. Additional choke data are shown starting at Table A-16 in Appendix A.

For a flow of 15,000 ft^3/s results indicated that interstitial flow effects dominated flow conditions near the crest. Velocities along the crest decreased significantly following choking to mid and fully choked levels. Full choke velocities decreased by an average of about 19 percent and as much as 29 percent from the no choke condition. Flow depth along the crest greatly increased with choking (Figure 29) indicating that the choke material reduced the amount of interstitial flow through the riprap immediately downstream of the crest.

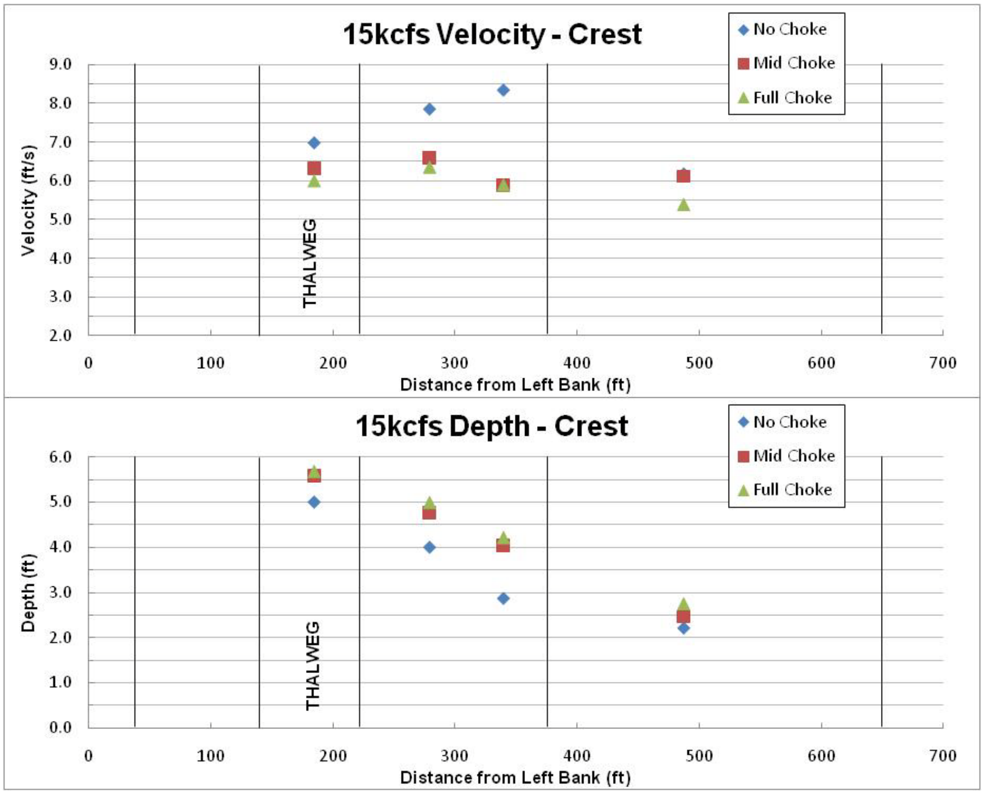


Figure 29. Comparison of velocity and depth data at the crest with different choked conditions at 15,000 ft^3/s; thalweg was not fully choked.

In contrast, flow further downstream was affected by change in relative surface roughness. Velocities increased significantly in the thalweg and also in critical passage areas to the right of the thalweg as the ramp was choked. Depths at the same locations increased only slightly (Figure 30). Differences in velocity and depth results both at the crest and downstream became less significant near the right bank as there was very little flow on that side of the ramp for this river flow.

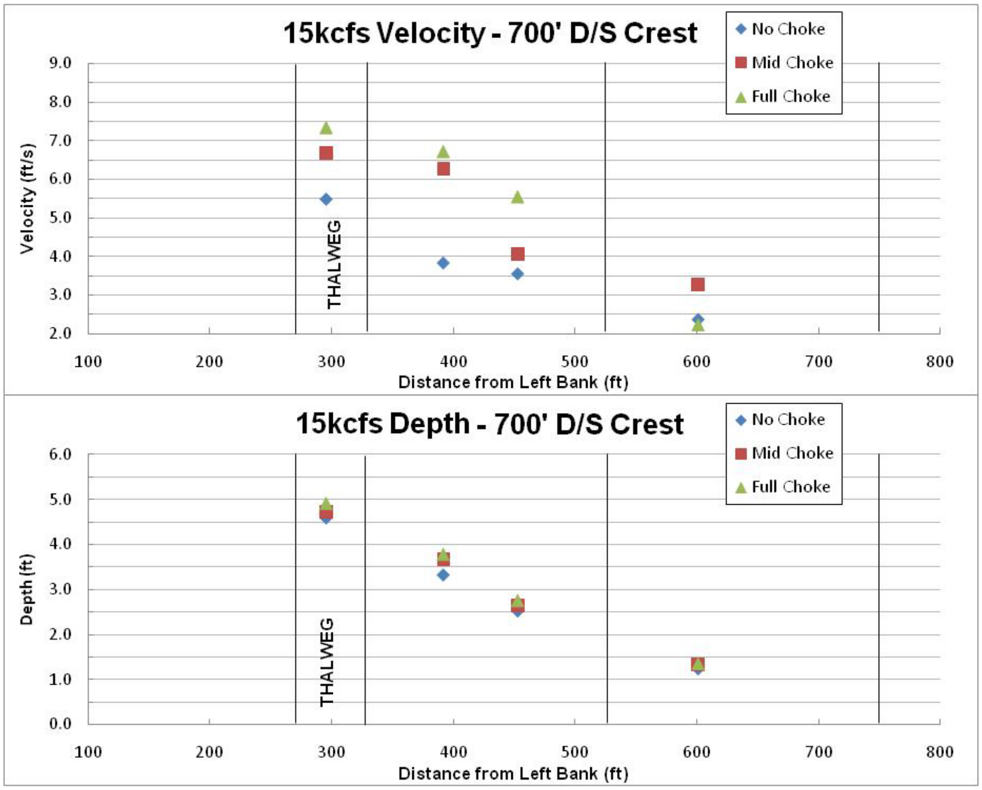


Figure 30. Comparison of velocity and depth data 700 ft downstream of the crest with different choked conditions at 15,000 ft^3/s; thalweg was not fully choked.

The trends observed at 15,000 ft^3/s were also found for higher flows of 30,000 ft^3/s and 40,000 ft^3/s (Figures 31 through 34). At the crest, velocities decreased and depth increased as choke material was added to the ramp. However, these differences became less significant as river flow increased. Crest velocities from the fully choked condition decreased by an average of 8 percent for 30,000 ft^3/s and only about 4.5 percent for 40,000 ft^3/s. Velocities on the downstream ramp surface increased significantly for both 30,000 and 40,000 ft^3/s (Figures 32 and 34). Mid and full choke results were similar in the thalweg, probably because the thalweg was never fully choked. Flow depths over most of the downstream ramp surface were similar for all choke conditions for both of these river flows.

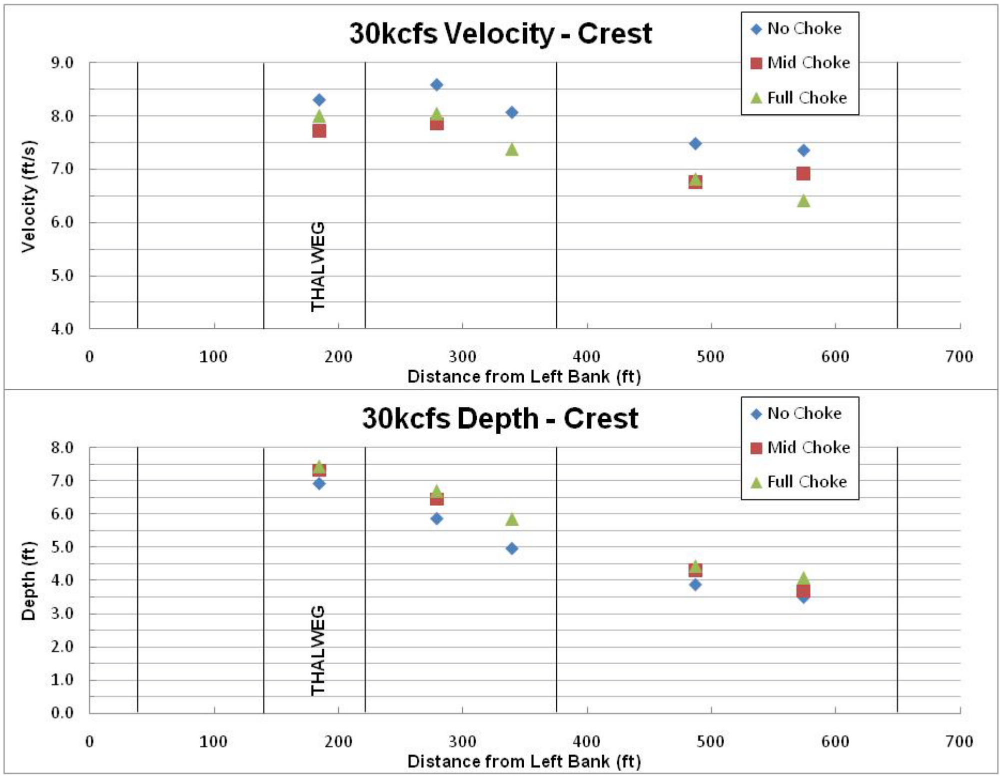


Figure 31. Comparison of velocity and depth data at the crest with different choked conditions at 30,000 ft^3/s; thalweg was not fully choked.

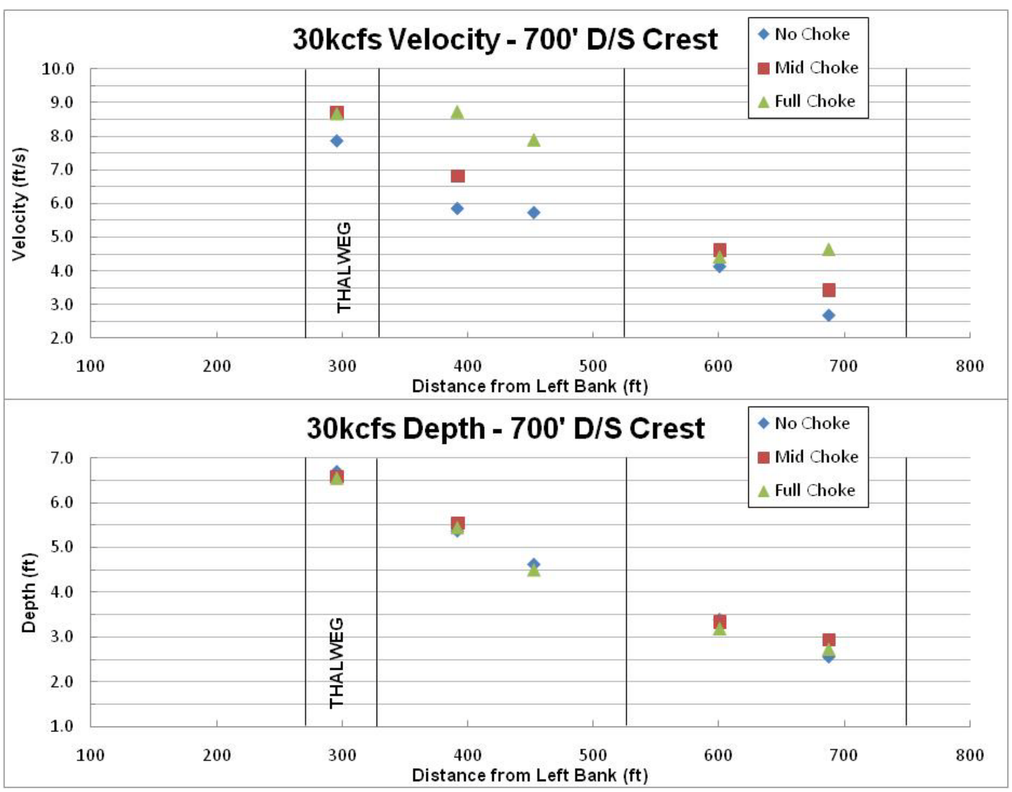


Figure 32 Comparison of velocity and depth data 700 ft downstream of the crest with different choked conditions at 30,000 ft^3/s; thalweg was not fully choked.

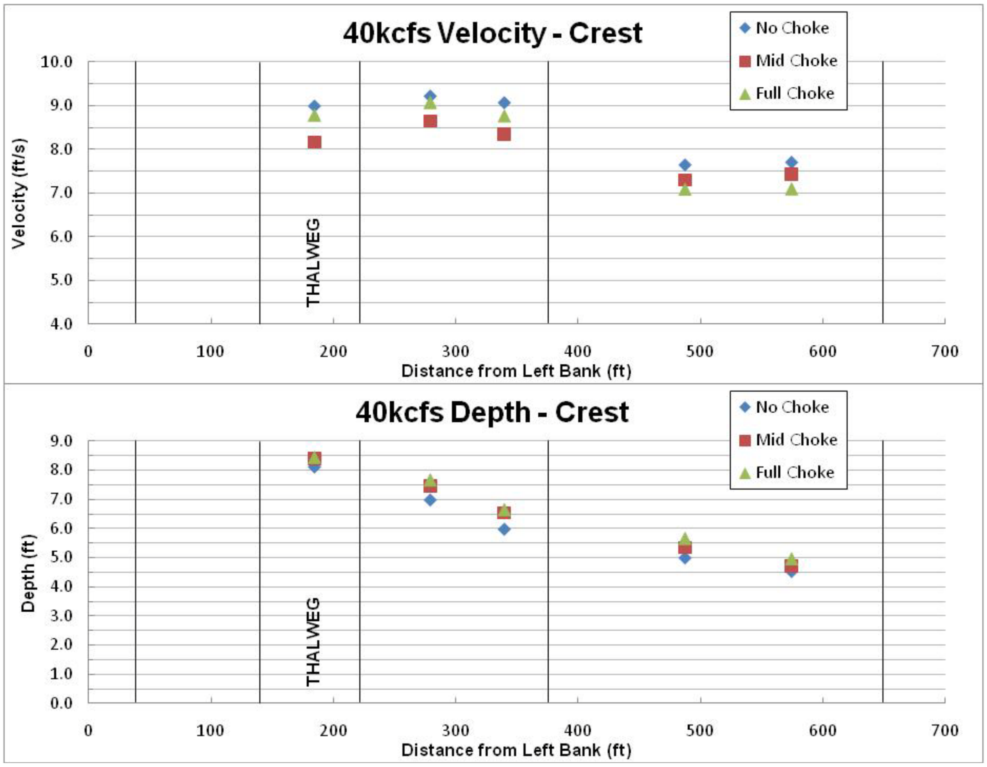


Figure 33. Comparison of velocity and depth data at the crest with different choked conditions at 40,000 ft^3/s; thalweg was not fully choked.

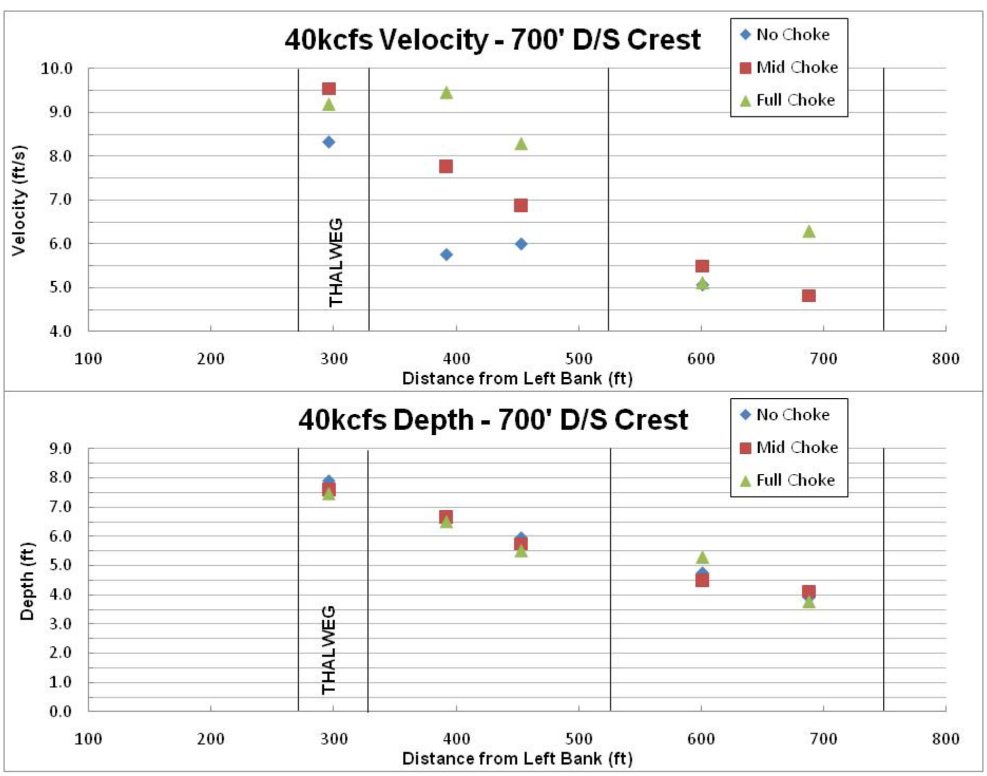


Figure 34. Comparison of velocity and depth data 700 ft downstream of the crest with different choked conditions at 40,000 ft^3/s; thalweg was not fully choked.

Visual observations showed that over time near-surface choke material was scoured from the rock matrix for a distance of about 100-200 ft downstream of the weir crest (Figure 35).

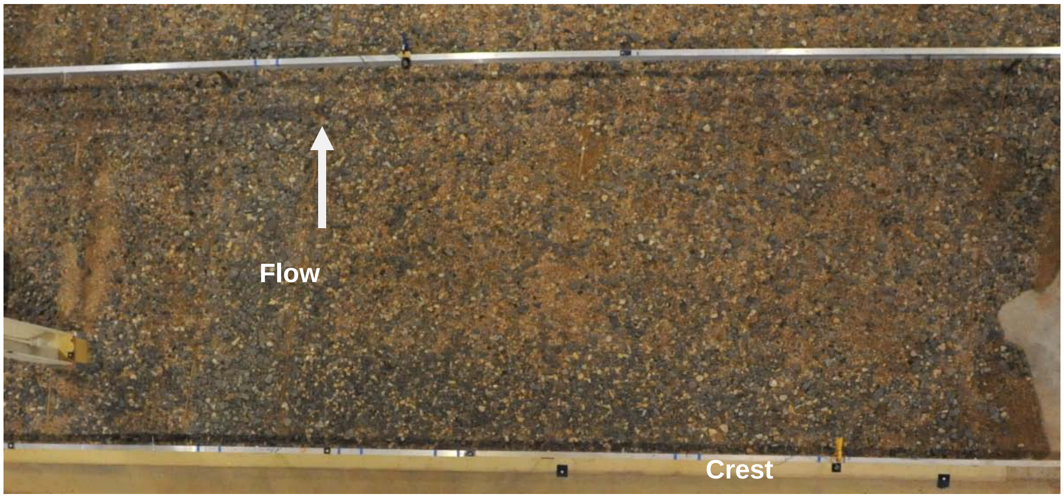


Figure 35. Scour of choke material immediately downstream of the crest over several days of water flowing over the fully choked model ramp.

Manning's n values that were computed for the three choked conditions are given in Table 3. The overall relative surface roughness decreased as choke material was added to the ramp. Table 3 represents the average roughness across the ramp at 700 ft downstream of the crest from the thalweg to the right bank. Average roughness of the majority of the ramp surface followed this same trend. Manning values from the physical model were slightly higher than the range simulated by the numerical models (0.032 to 0.043).

Table 3. Manning's n values resulting from three choked conditions in the physical model.

Flow	**Manning n value**		
cfs	**No Choke**	**Mid Choke**	**Full Choke**
7,000	0.043	0.041	0.038
15,000	0.043	0.035	0.036
30,000	0.042	0.041	0.035
40,000	0.048	0.041	0.037
70,000	0.049	0.043	0.040
Avg.	**0.045**	**0.040**	**0.037**

Choked Ramp Discussion

Flow over the crest and immediately downstream was significantly influenced by the choke material. The increase in depth, which is inconsistent with a reduction in surface roughness, is attributed to a loss of surface flow to interstitial flow for the no-choke condition followed by a reduction in interstitial flow following choking.

The area just downstream of the crest would likely exhibit a greater percentage of interstitial flow compared to the downstream ramp due to the locally increased angle of attack as flow passes over the crest. This was evident by the scoured choke material downstream of the crest. Initially, the choke material suppressed interstitial flow and caused the ramp surface to more closely represent a solid boundary which resulted in locally increased depths and decreased velocities. Despite these changes, flow over the crest is a concern for fish passage which may require additional features to further reduce velocities in strategic areas near the crest.

Further downstream on the ramp, flow conditions were affected by changes in relative surface roughness which decreased as choke material was added. Flow depth generally decreased one-half foot or less between no-choked and fully-choked conditions. Flow velocity showed an increase of 2 to 3 ft/s in many locations for the fully choked riprap. There was little difference in the thalweg velocities between ramp mid and full choke conditions, likely due to the thalweg never being fully choked. Despite increased velocities in areas to the right of the thalweg, results indicate that fish passage corridors remain available where both velocity and depth passage criteria are met. These corridors moved closer to the right bank as river flow increased due to higher velocities near midstream and increased flow depth available near the bank.

Ramp Passage Optimization

Results from diversion and choking tests revealed that velocities at the weir crest and immediately downstream posed the greatest concern to fish passage. Tests of boulder fields located on the upper right side of the ramp from the crest downstream 500 ft were conducted to evaluate this method for expanding the ramp area meeting flow criteria for passage (Figure 36). Seven iterations (grids) of boulder fields were tested at 30,000 ft^3/s which were narrowed down to one recommended design (Appendix B).

Passage Optimization Results

Initially, a boulder field was tested covering an area from the thalweg to the right bank extending approximately 500 ft downstream from the crest. Tests were run of boulders spaced approximately 60, 50, and then 25 ft from each other (grids 1-3). Boulder spacing of 60 and 50 ft failed to provide sufficient reduction in flow velocity to meet passage objectives. The 25 ft spacing was found to provide about a 1 ft/s reduction in the average velocity within the boulder field compared to the ramp without boulders.

The area of the boulder field was then reduced by limiting the field to the right slope only. This configuration, shown as Grid 4 in Figure 36, spanned about 300 ft across the river from the right bank and followed the right slope break about 500 ft downstream from the crest. Boulders were spaced at about 5 boulder diameters (25 to 30 ft) with the first row placed about 50 ft downstream of the crest. Grid 4 caused crest velocities to decrease on the right side of the weir by 0.5 to 0.75 ft/s. This resulted in increased velocities in the thalweg by up to 0.7 ft/s. Grid 4 was also tested at a width of 200 ft which produced similar results. This configuration was again tested with a width of only 100 ft which was not as successful at decreasing crest velocities.

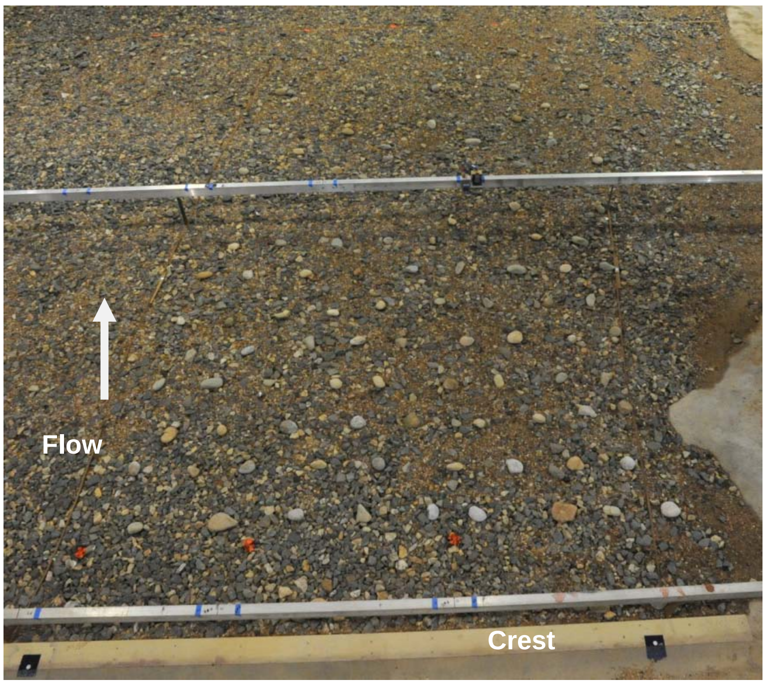


Figure 36. Grid 4 300 ft width - boulder field tested near the right bank and immediately downstream of the diversion weir.

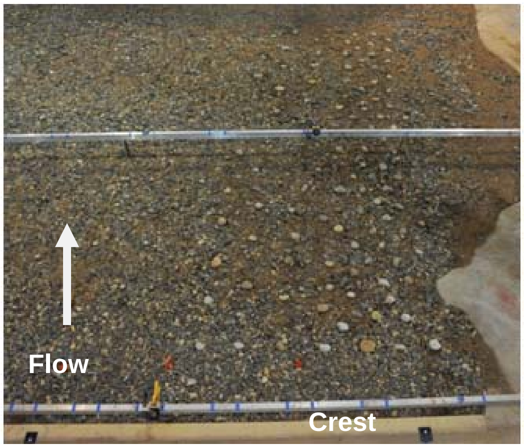
Boulder Grid 5

Results from Grid 4 led to Grid 5 which is shown in Figure 37 (a). This configuration spanned 200 ft from the right bank and extended 500 ft downstream similar to Grid 4. Boulders within the right 100 ft were spaced 3 boulder diameters apart and the left 100 ft were spaced 5 boulder diameters apart. Figure 38 shows Grid 5 reduced crest velocities by up to 0.6 ft/s on the right side of the crest and increased them by 0.7 ft/s in the thalweg.

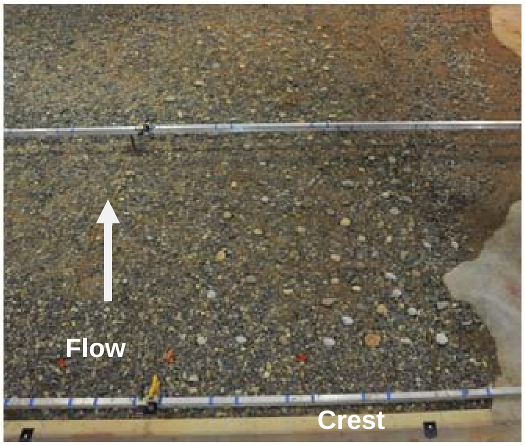
Dye testing indicated that there was a significant shear zone with a high velocity gradient located on the left side of the boulder field particularly on the downstream half. At 450 ft from the left bank (left edge of boulder field) and 250 to 500 ft downstream of the crest, the average velocity was about 8 ft/s. Dye inserted at this location flowed straight downstream and little dispersion was observed. When dye was inserted at 570 ft from the left bank velocities from 250 to 500 ft downstream were only about 4 ft/s (Table 4) and the dye dispersed throughout the boulder field.

Boulder Grid 6

Results from Grid 5 dye tests resulted in shifting the downstream half of the boulder field to the left by 100 ft. Figure 37 (b) illustrates how Grid 6 is the same as the previous boulder field but with the last 250 ft shifted over to the left slope break. Boulders in Grid 6 reduced right side crest velocities by up to 0.65 ft/s, leaving a 150 ft wide section on the crest where velocities were less than 6 ft/s (Figure 41). Thalweg velocity increased by 0.54 ft/s.



(a)



(b)

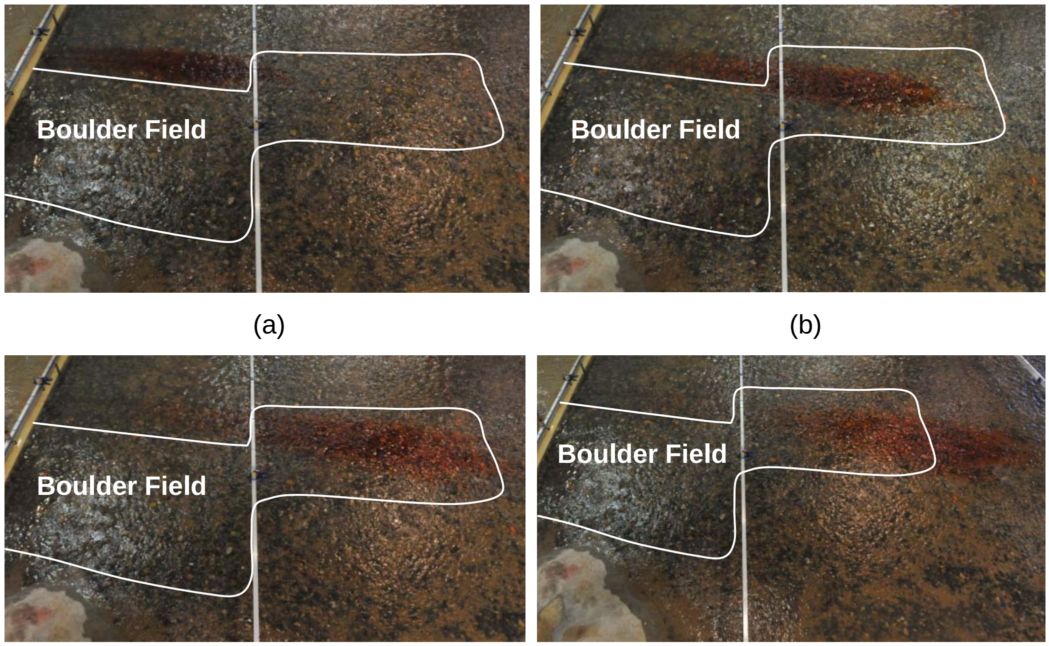
Figure 37. Boulder Grids 5 (a) and 6 (b) near the right bank of the ramp.

Dye tests showed that shifting the bottom half of the boulder field to the left caused the shear layer to be moved closer to the thalweg, increasing the width of the passage corridor. Table 4 shows that the average velocity near the left edge of the boulder field (450 ft) was reduced by 1.5 ft/s by the Grid 6 configuration. Velocities closer to the right bank were only slightly reduced.

Table 4. Average velocities in upper and lower halves of boulder fields, Grid 5 and 6, 30,000 ft^3/s river flow.

Dye insertion at crest	**0 - 250 D/S Crest**		**250 - 500 ft D/S Crest**	
Distance from Left Bank	**Grid 5 Velocity**	**Grid 6 Velocity**	**Grid 5 Velocity**	**Grid 6 Velocity**
ft	*ft/s*	*ft/s*	*ft/s*	*ft/s*
448	8.7	8.2	**8.0**	**6.5**
573	8.3	6.8	4.2	3.7
675	7.6	6.3	4.4	3.9

Dye tests in Figure 38 illustrate how the flow was dispersed by the Grid 6 boulder field. The dye was inserted at approximately 425 ft from the left bank and remained concentrated until it was more than 250 ft downstream which is marked by the second aluminum channel shown in the middle of the photos. Past that point the flow met the downstream section of the boulder field that has been shifted over. This resulted in dispersed flow and decreased velocities which were visually apparent in the model. Flow downstream of the boulders near the right bank was also influenced by the boulder field as seen in Figure 39.



(a) (b) (c) (d)

Figure 38. Dye tests near the left edge of the Grid 6 boulder field. Photographs are looking at boulder field from the right bank. White outline shows approximate boulder field location with water flowing to the right.

Plan view velocity data with and without a boulder field at 30,000 ft^3/s are shown in Figures 39 and 40 respectively. Passage ways where BRT velocity criteria are met (less than 6 ft/s) are marked by the green hatch shown on the figures. The boulder field shown (Grid 6) provided a continuous passage corridor up the ramp and over the weir crest. Its influence can be seen by 4 ft/s velocities for at least another 400 ft downstream of the boulder field. Although both passage ways near the right bank appear similar, the one without a boulder field is clearly cut off at approximately 100 - 200 ft downstream of the crest near the right.

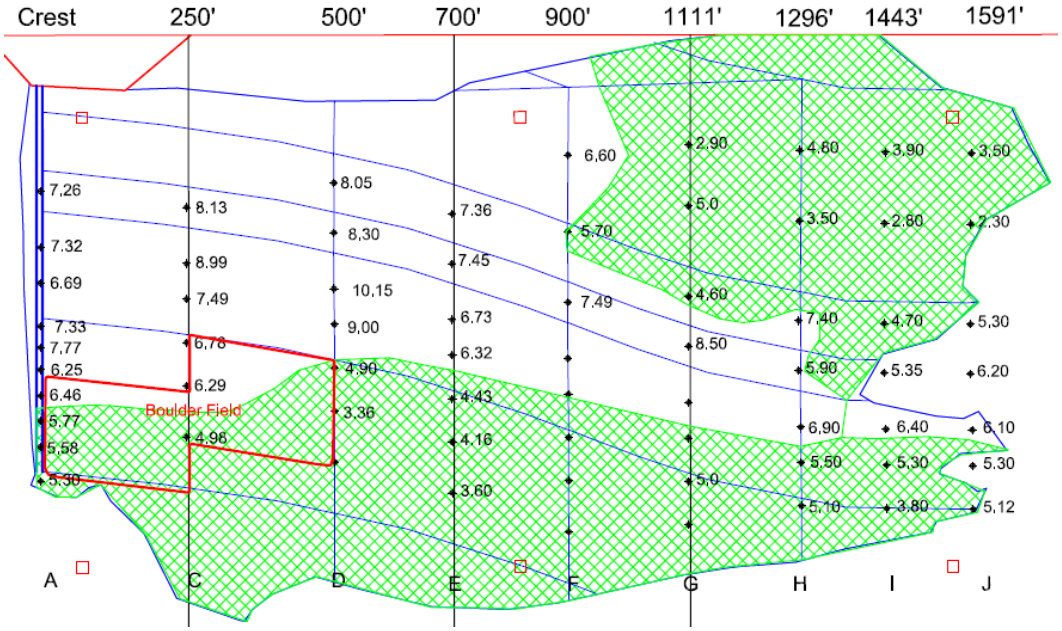


Figure 39. Grid 6 velocity data at 30,000 ft^3/s (boulder field extents outlined in red). Green hatched areas show where the velocity is less than 6 ft/s.

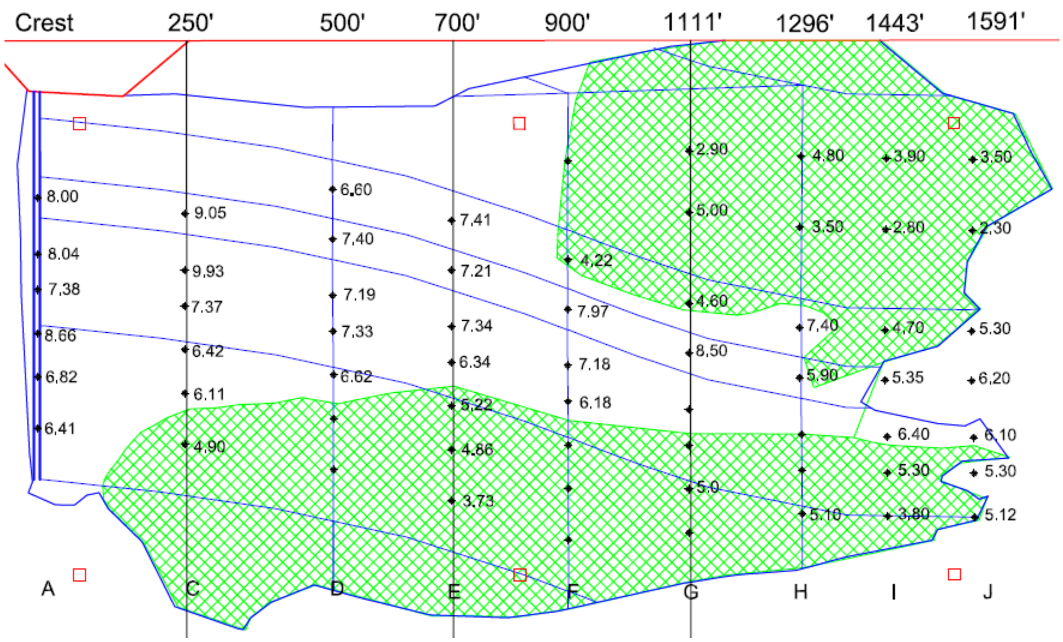


Figure 40. Velocity data at 30,000 ft^3/s with no boulder field. Green hatched areas show where the velocity is less than 6 ft/s.

Boulder Grid 7

Grid 7 was an attempt to further reduce crest velocities as well as reduce flow through the downstream end of the boulder field. An additional row of boulders was added just 25 ft below the crest and the entire downstream half of the field was increased to 3 boulder diameter spacing. As shown in Figure 41 no significant improvements were made using additional boulders. The same was true for downstream flow dispersion.

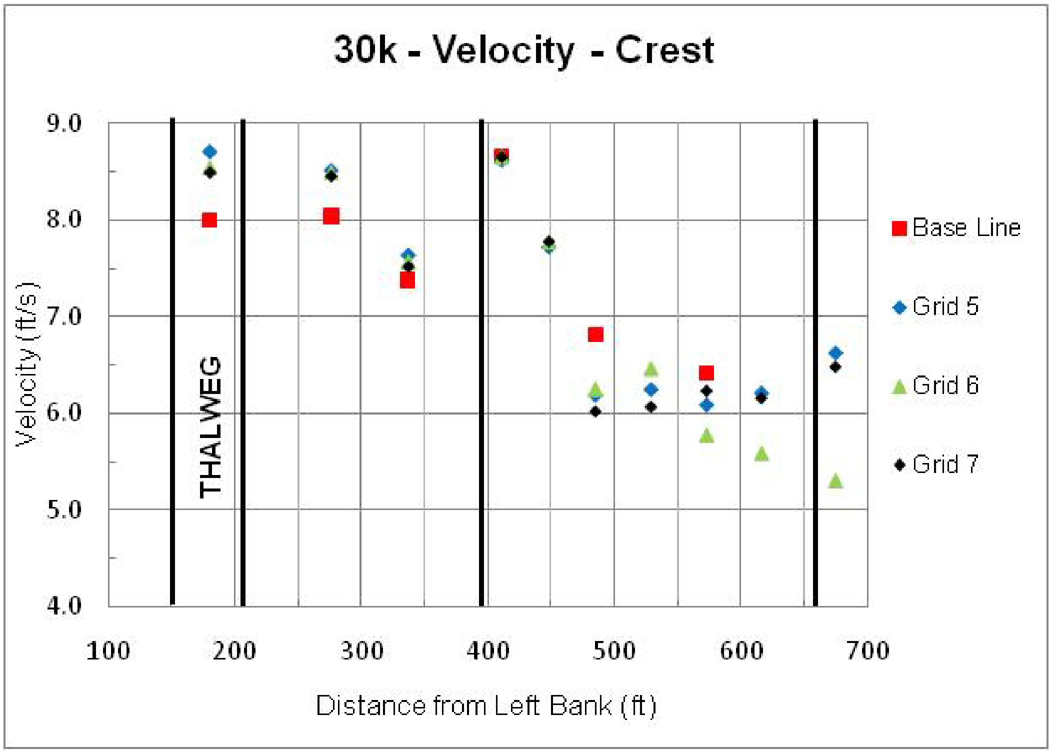


Figure 41. Resulting crest velocities from boulder field testing.

As shown in Figure 42 the boulder fields did not have a significant impact on flow depth over the crest.

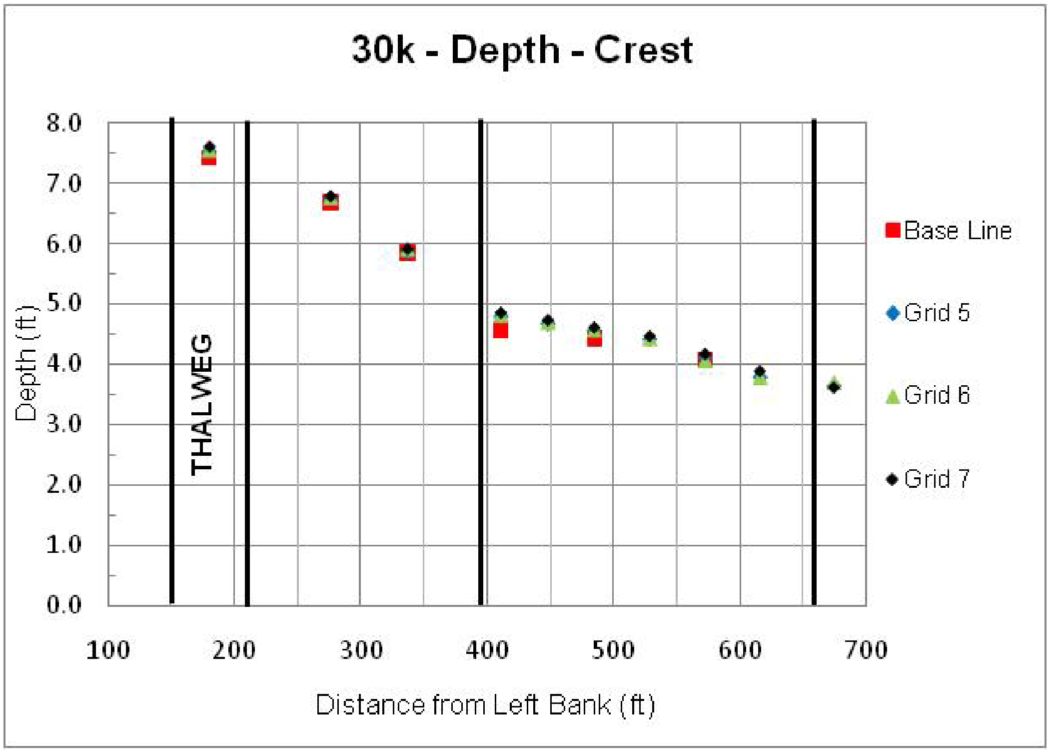
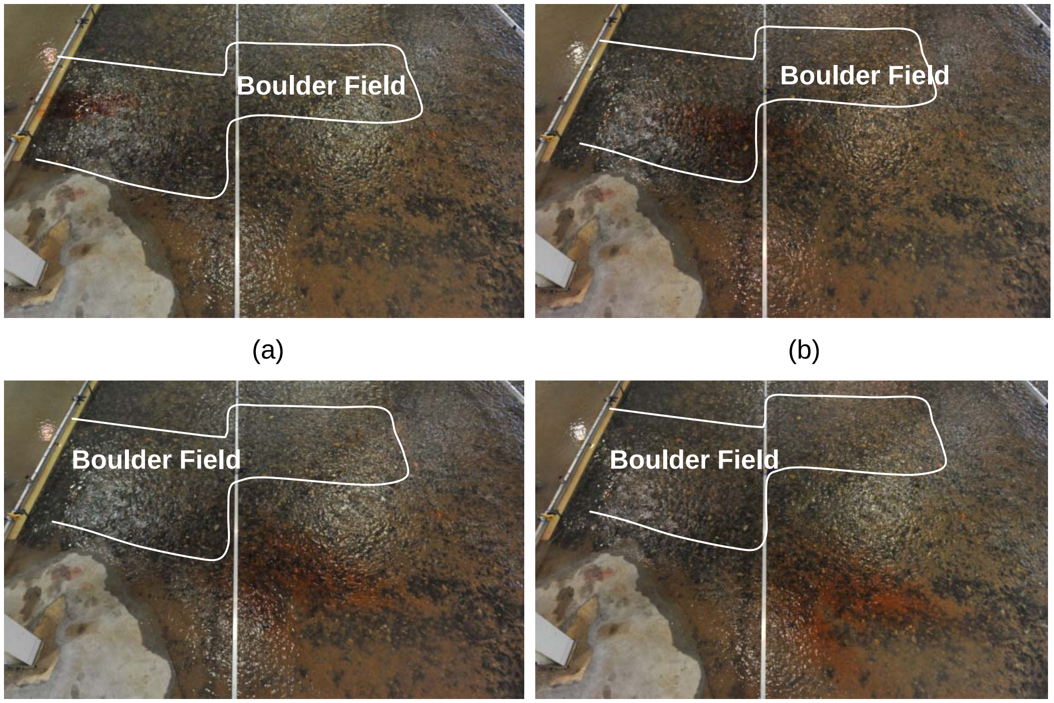


Figure 42. Resulting flow depths on the crest from boulder field testing.

General Dye Testing

Dye tests revealed that Grids 5, 6, and 7 were all effective in dispersing flow and decreasing velocities within about 200 ft from the right bank. When dye was injected within this distance from the right bank it was immediately dispersed throughout the boulder field (Figure 40a and b). In general the flow moved through the boulders at a slight angle towards the right bank and noticeably slowed down at about 250 ft downstream (Figure 40c and d). A very slow moving eddy formed in the area that protrudes from the bank, immediately downstream of the knob.



(a) (b) (c) (d)

Figure 43. Dye testing. Photographs are looking at boulder field from the right bank, immediately downstream of the crest. Approximate boulder field location shown in white outline with water flowing to the right.

Passage Optimization Discussion

Several boulder field configurations were tested before one was found that yielded positive results. However, the results from these early configurations provided insight as to how a boulder field should be applied to this particular ramp. Fields that extended from the thalweg to the right bank increased roughness slightly but were largely ineffective in moving flow away from the desired passage area. Grid 4 revealed that increasing the roughness density in a smaller section on the right side of the ramp provided a wider, smoother area on the left for the flow to pass. Testing showed that for this ramp the optimum boulder field width was 200 ft. A wider field was less effective at moving the flow to the thalweg and smaller fields were less effective at reducing crest velocities.

Grid 6 produced the best results and is recommended for implementation in the prototype ramp. The 100 ft width of 3 diameters spacing (center to center) on the right helped reduce crest velocities near the right bank and push more flow to the center of the ramp. Shifting the downstream section of the boulder field inward was effective in providing a potentially wider passage corridor. This shift resulted in an additional 100 ft width with velocities about 6 ft/s or less and moved the shear layer with high velocities closer to the thalweg. The boulder field will also provide additional diversity to passage ways over the ramp. Passage diversity is important as the ramp will be used by many other fish species besides Pallids.

Adding a boulder field along the right side of the channel was found to alter the flow distribution across the ramp. Grid 6 increased the water surface elevation at the canal headworks by 0.16 ft and ramp thalweg velocities by 0.75 ft/s. Another concern is that the turbulence caused by the boulders will deter the sturgeon from passing up the ramp. Shear layers formed as the water passed around the boulders creating a high velocity gradient through which the fish would have to pass as they maneuver their way up the boulder field.

Despite possible negative side effects, the ability to influence flow at the crest and other areas critical to passage using a boulder field is encouraging. Reducing crest velocities to below 6 ft/s at a critical passage flow is a step in the right direction but additional input from the BRT and other fish experts is needed to determine if these results are acceptable for pallid sturgeon. Depth is less of a concern as it is not as critical as velocity and there were no significant changes at the crest.

Shortened Ramp with Steepened Toe – Concept 2 (C2)

The C1 ramp was modified by shortening the ramp and steepening the toe to where it meets the existing river channel at about 1300 ft downstream from the crest. The steepened toe reduced the ramp surface area by about 21 percent compared to the C1 ramp. Figure 44 shows the shortened C2 ramp in the physical model with the white outline indicating where the rock ramp meets the existing river bottom. The wood templates represent the topography lines and show how the left side of the ramp slopes inward and downstream.

Velocity and depth data were collected over the entire C2 ramp at the same locations as the C1 ramp. There were no significant differences in results on the crest and upstream half of the ramp. Therefore results are only presented at cross-sections 700, 900, 1,111, and 1,296 ft downstream from the crest. It should be noted that results shown here were taken with the Grid 6 boulder field in place. Appendix C contains results of the shortened ramp without a boulder field. The boulders did not have a significant impact results near the downstream end of the ramp where efforts in this section were focused. Data from the C1 and C2 ramps at these downstream cross-sections are compared in Figures 45-52. The charts show data at each cross-section, looking downstream where the vertical black lines indicate breaks in slope across the ramp. Planview plots illustrate areas where velocities were within BRT criteria (less than 6 ft/s).

Results from the ADH numerical model produced by the COE were similar to physical model results. Generally, both models showed increased velocities in steepened areas on the left side of the ramp, upstream from the toe. Both models also showed that critical passage corridors with acceptable velocity and depth are maintained on the right side of the ramp. However, physical model results showed greater depths and lower velocities near the ramp toe and in certain areas on the right side of the ramp.

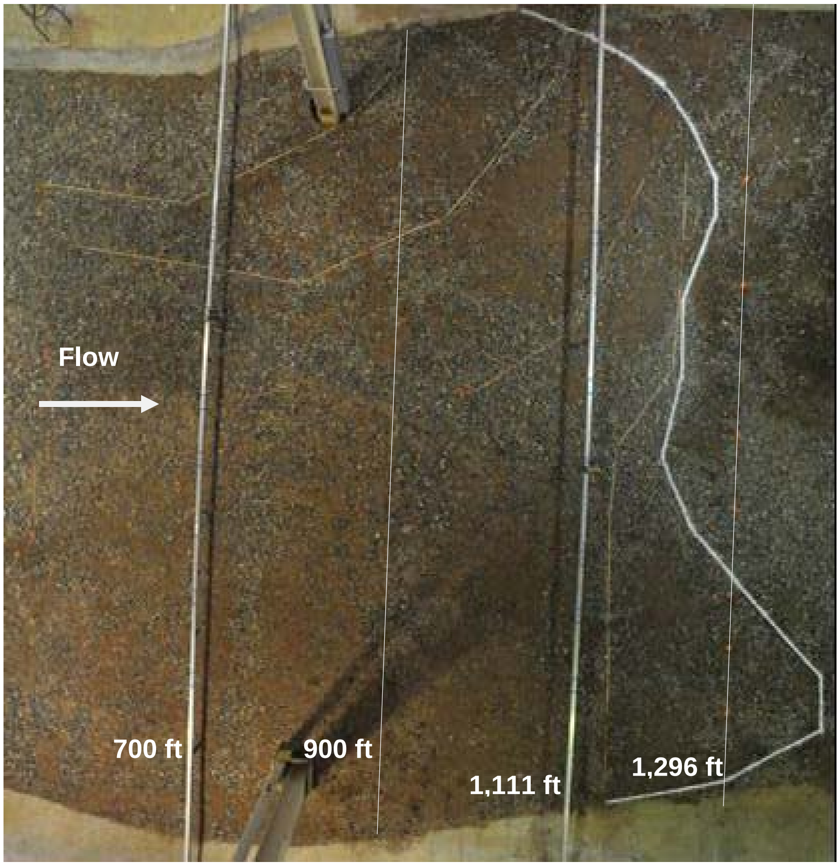


Figure 44. Shortened version of the rock ramp tested in the physical model, stationing shows distance downstream from crest.

Ramp C2 Results

15,000 cfs

In general, C2 ramp velocities were slightly lower than the C1 ramp (Figure 45). C2 ramp velocities near the ramp toe were particularly greater except for in the thalweg. Results shown in Figure 46 illustrate that the area where velocity was less than 6 ft/s was not changed by the shortened ramp. Data taken at 900 ft downstream are not presented here as a wood template at that location in the model produced artificially high velocities. Also a few data points are missing from the C1 ramp or are unreasonably low. This problem was resolved for data from other flows presented here.

At 700 ft downstream C1 ramp depths were greater than C2 ramp by an average of 0.40 ft. Depths at 1,111 ft downstream were about the same for both ramps. However, C2 ramp depths at 1,296 ft were greater than those from the C1 ramp by an average of 1.1 ft.

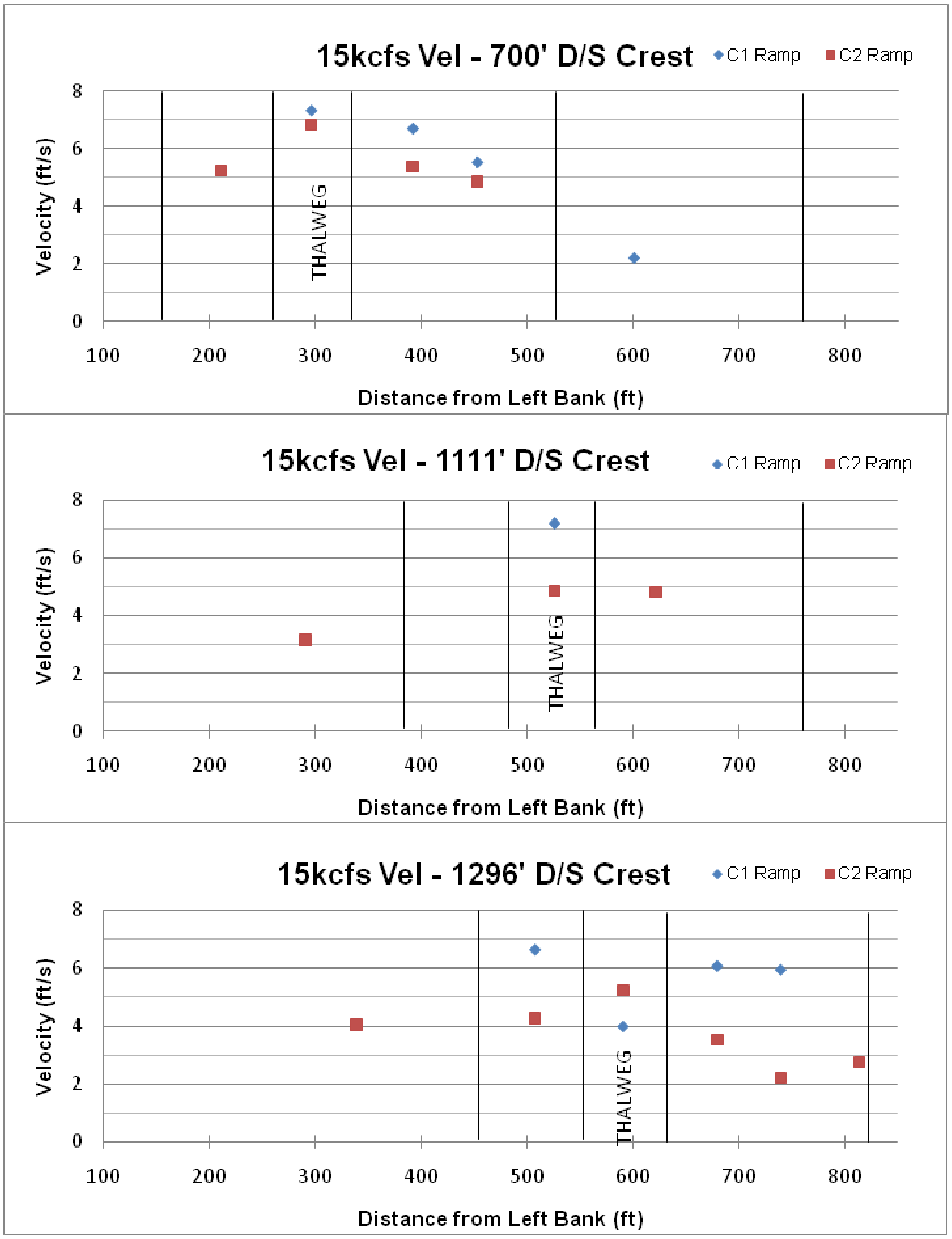


Figure 45. Comparison of C1 and C2 ramp flow velocities for 15,000 ft^3/s at 700, 1111, and 1296 ft downstream of the crest.

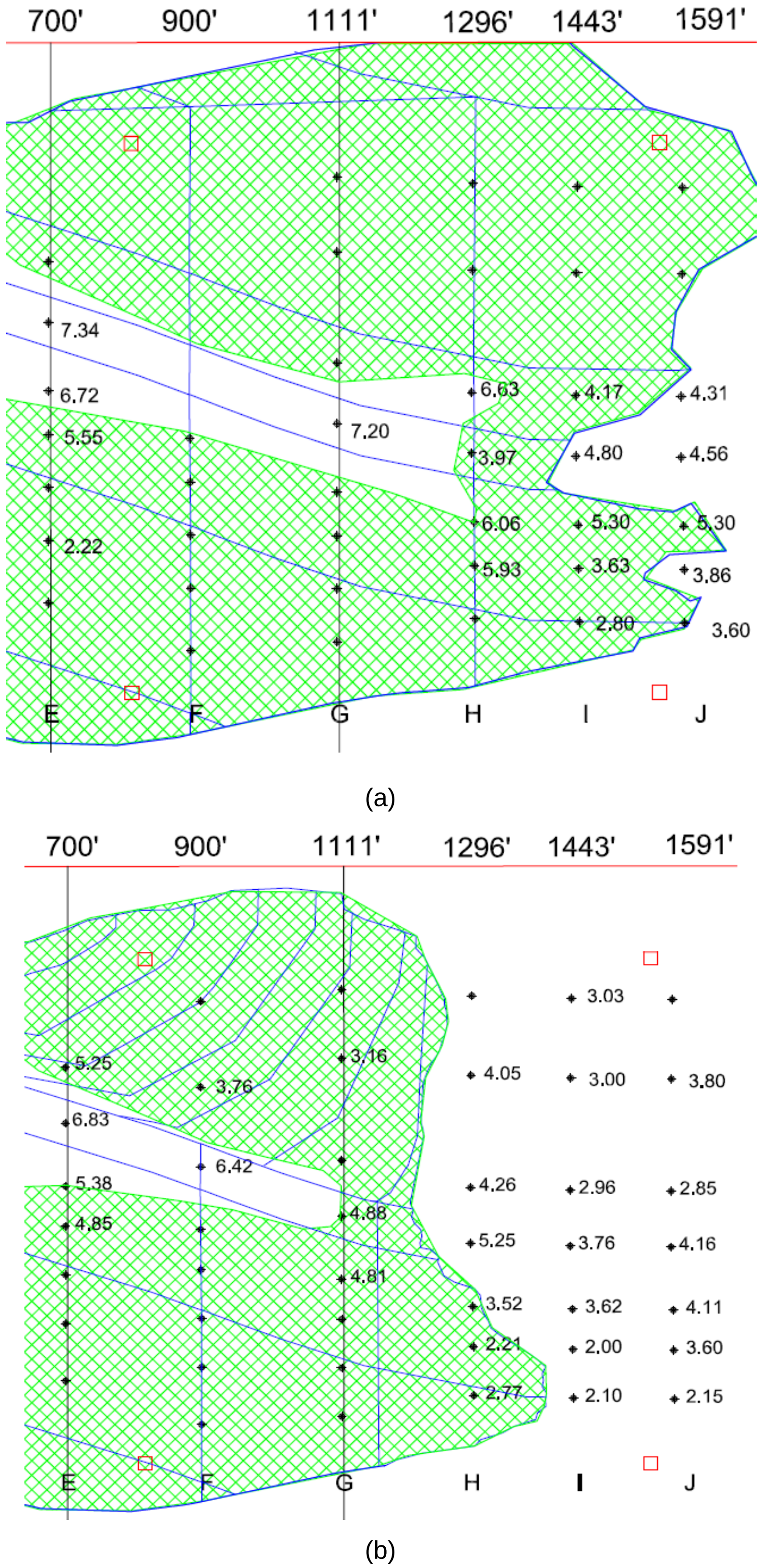


Figure 46. 15,000 ft^3/s velocity data from the C1 ramp (a) compared to the C2 ramp (b); green hatch indicates areas on the ramp where velocity was less than 6 ft/s.

30,000 cfs

At 30,000 ft^3/s, the C2 ramp continued to show lower velocities compared to the longer C1 ramp as shown in Figure 47. At 700 ft downstream data on the left side of the thalweg from the C1 ramp are not available. However, it is expected that they would follow the trend shown at 1,111 ft where C2 velocities were greater than those from the C1 ramp on the steepened portion of the left side of the ramp. That trend began to reverse at 1,296 ft downstream, particularly near the right bank where C1 ramp velocities exceeded those from the shortened ramp (Figure 47).

Figure 48 compares areas where velocity is within BRT criteria from both ramp concepts. Results showed that C2 ramp areas were greatly reduced where the slope was steepened to the left of the thalweg. However, a critical passage corridor on the right side of the ramp was not changed.

Depths from both ramps were very similar at 700 ft downstream from the crest. At 1,111 ft downstream C2 ramp depths were greater by an average of 1 ft to the left of the thalweg and 0.30 ft less on the right side of the thalweg in comparison to the C1 ramp. At 1,296 ft shortened ramp depths exceeded those from the longer C1 ramp by an average of almost 2 ft at the same distance downstream.

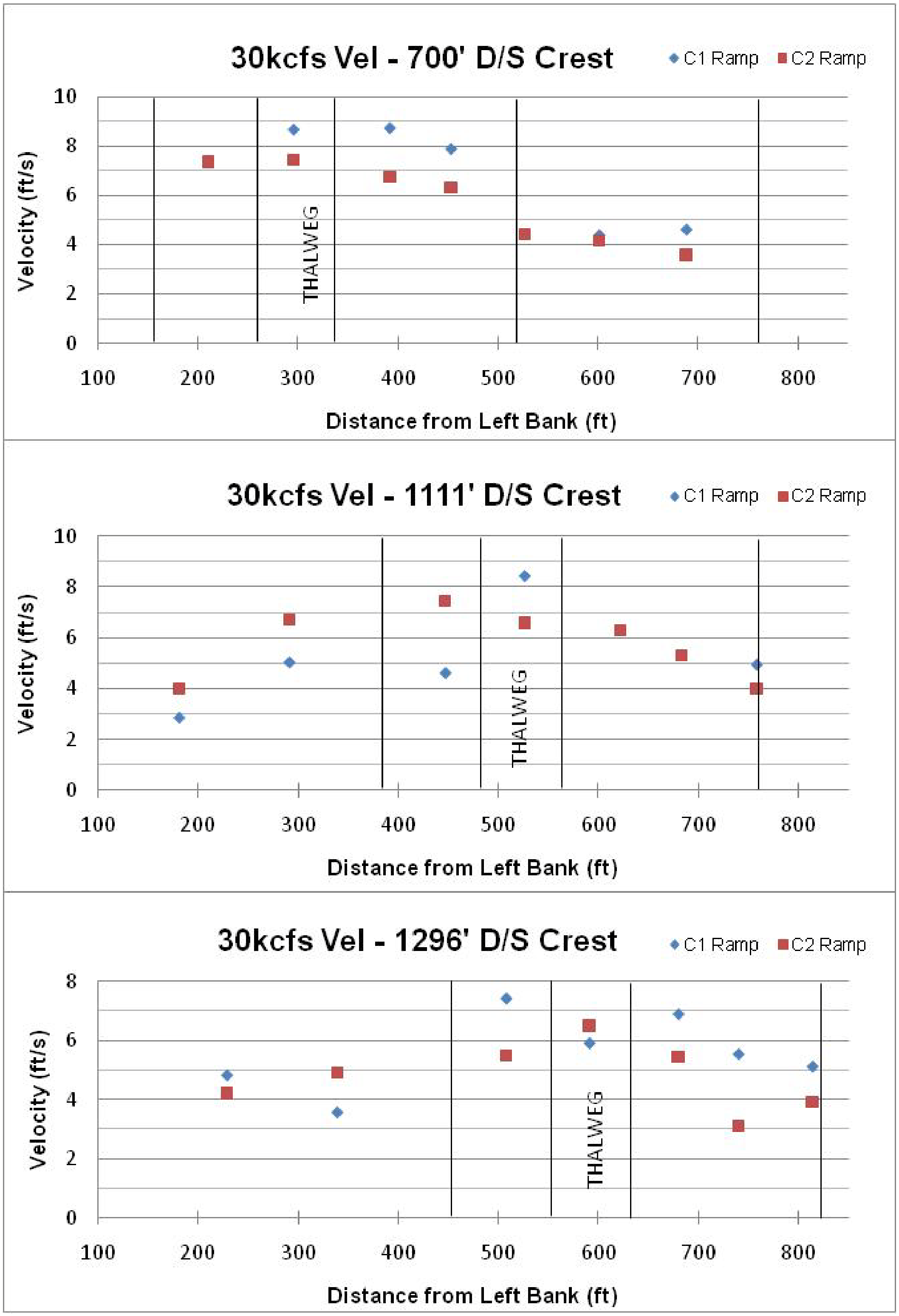


Figure 47. Comparison of original and modified ramp velocities of 30,000 ft^3/s at 700, 1111, and 1296 ft downstream of the crest.

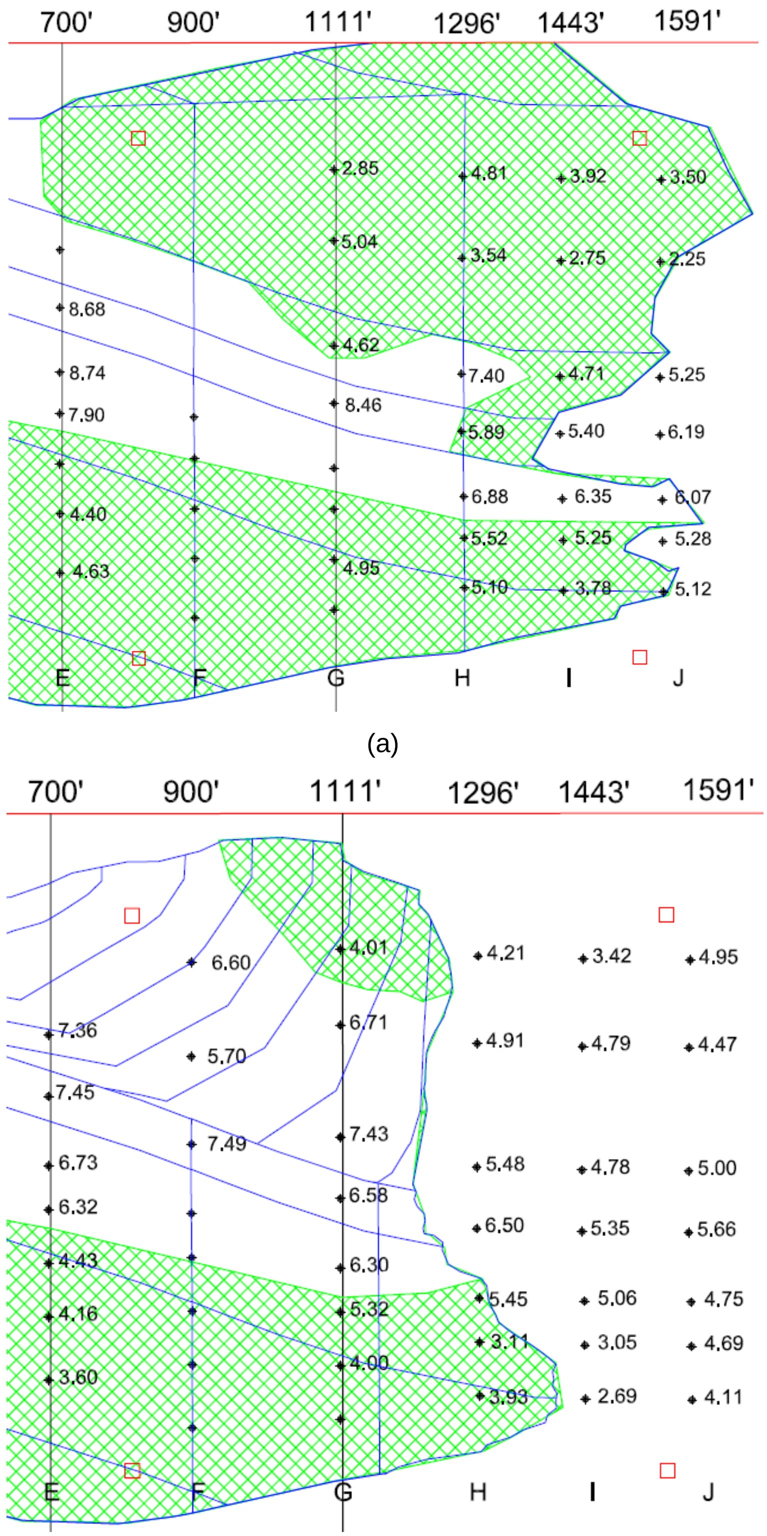


Figure 48. 30,000 ft^3/s velocity data from the C1 ramp (a) compared to the shortened C2 ramp (b); green hatch indicates areas on the ramp where velocity was less than 6 ft/s.

40,000 cfs

Velocity trends at 40,000 ft^3/s river flow closely resembled those observed for 30,000 ft^3/s. At 1,111 ft C2 ramp velocities were consistently higher across the ramp except for in the thalweg where velocities were lower than found in the C1 ramp (Figure 49). More uniform velocity data at 1,111 ft indicate that the distance downstream where profiles begin to level out moves further upstream with increasing river flow. Although velocity trends appear similar to 30,000 cfs, velocity profiles begin to change at some point between 900 and 1,000 ft downstream for this flow. Lower C2 ramp velocities allow the passage corridor on the right side to be maintained (Figure 50).

Depth trends at this flow were also very similar to those at 30,000 cfs. At 700 ft downstream C1 ramp depths were deeper by an average of 0.42 ft. At 1,111 and 1,296 ft shortened ramp depths were deeper than the C1 ramp on average by 0.7 and 1.9 ft, respectively.

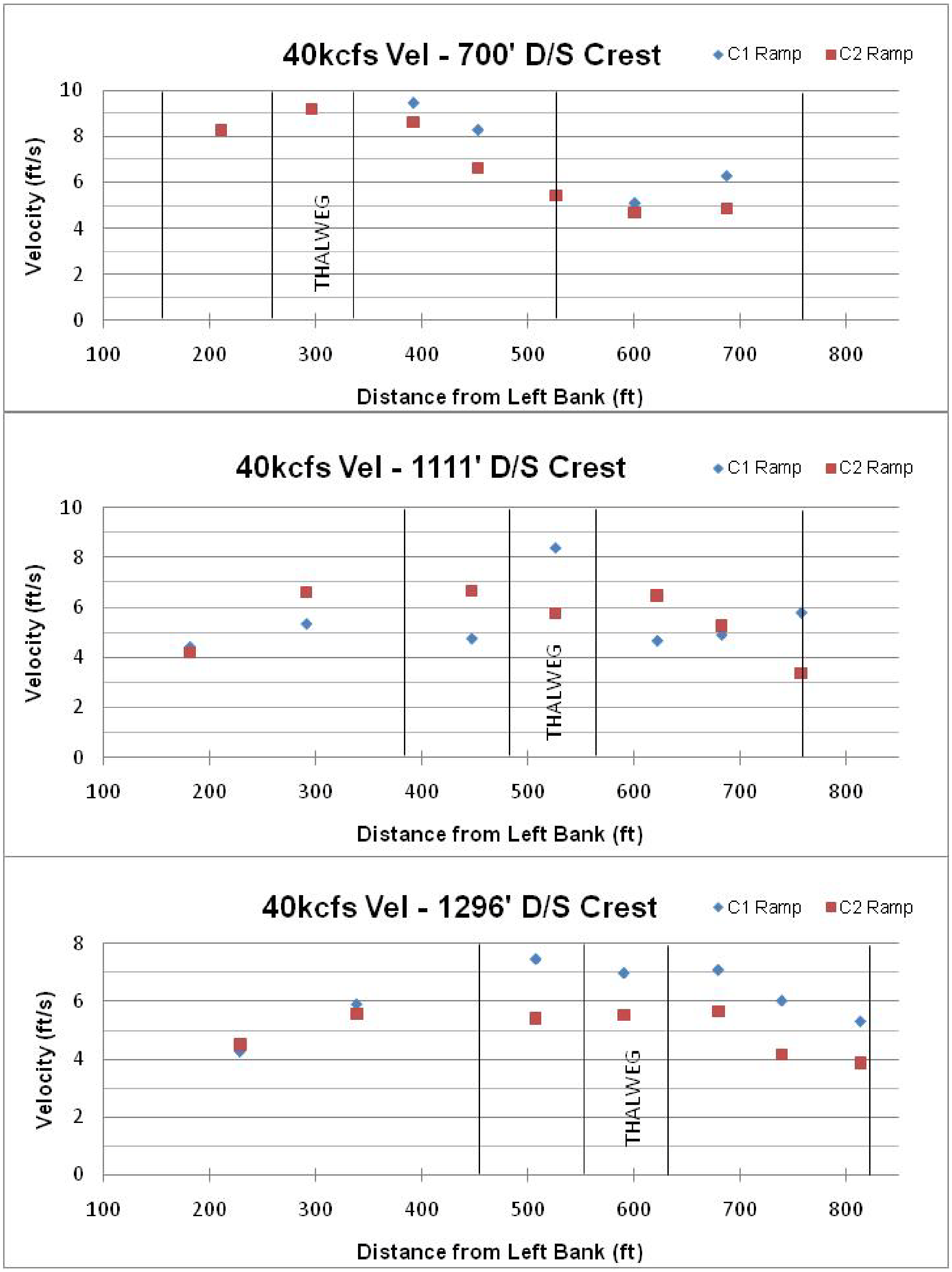


Figure 49. Comparison of original and modified ramp velocities of 40,000 ft^3/s at 700, 1111, and 1296 ft downstream of the crest.

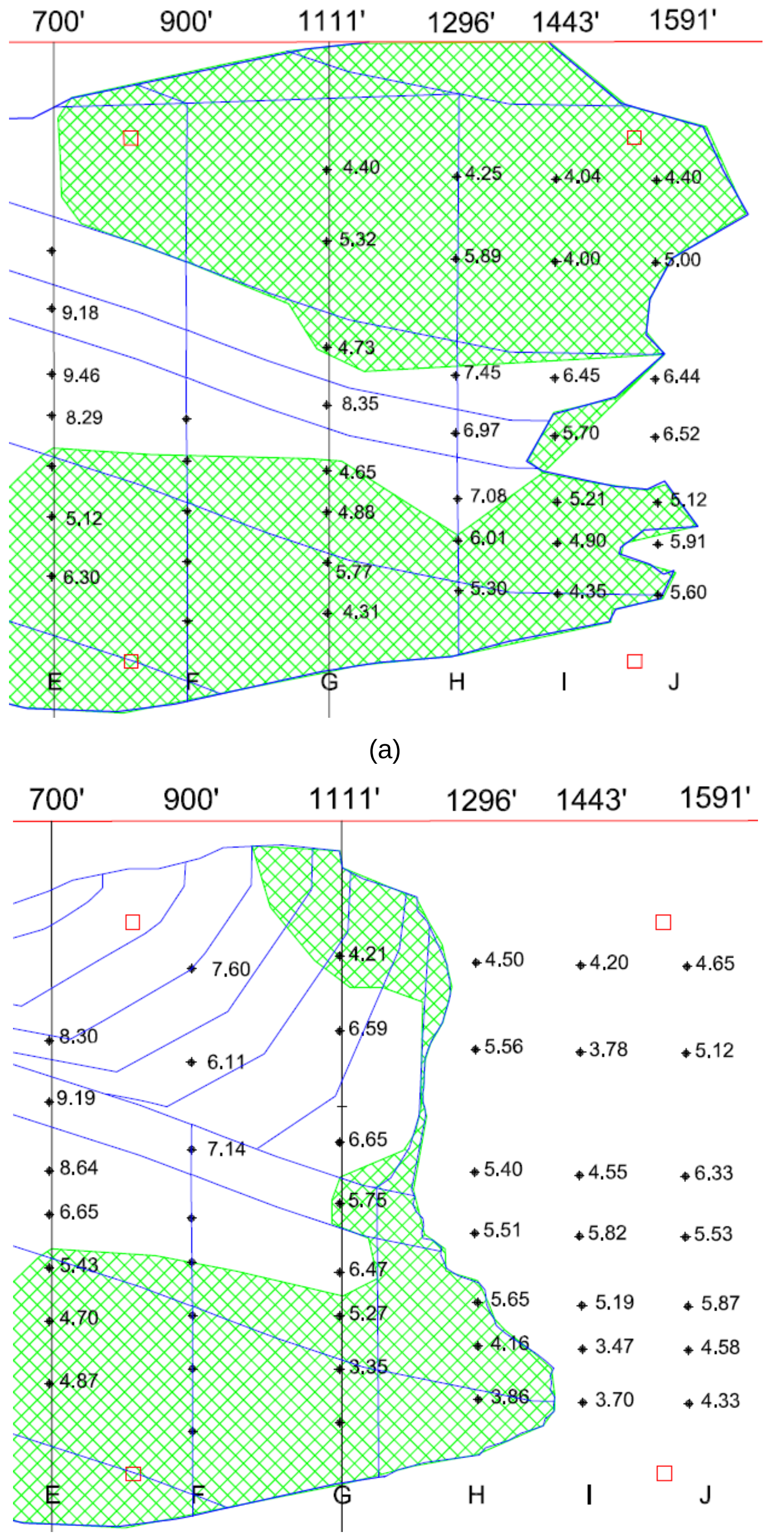


Figure 50. 40,000 ft^3/s velocity data from the C1 ramp (a) compared to the shortened C2 ramp (b); green hatch indicates areas on the ramp where velocity was less than 6 ft/s.

70,000 cfs

Figure 51 shows that C2 velocity data were again consistently lower at 700 ft downstream. Results from both ramps were similar at 1,111 ft with the exception of the left side where C2 velocities were greater than the C1 ramp. At 1,296 ft downstream C2 results were again lower than the longer ramp, particularly on the right side of the thalweg. As with the other flows, the passage corridor near the right bank did not change with the shortened version of the ramp (Figure 52).

Depth trends at this flow continued to match those from other flows. At 700 ft downstream C1 ramp depths were deeper by an average of only 0.1 ft. At 1,111 and 1,296 ft C2 ramp depths were deeper than the longer ramp on average by 0.6 and 2 ft, respectively.

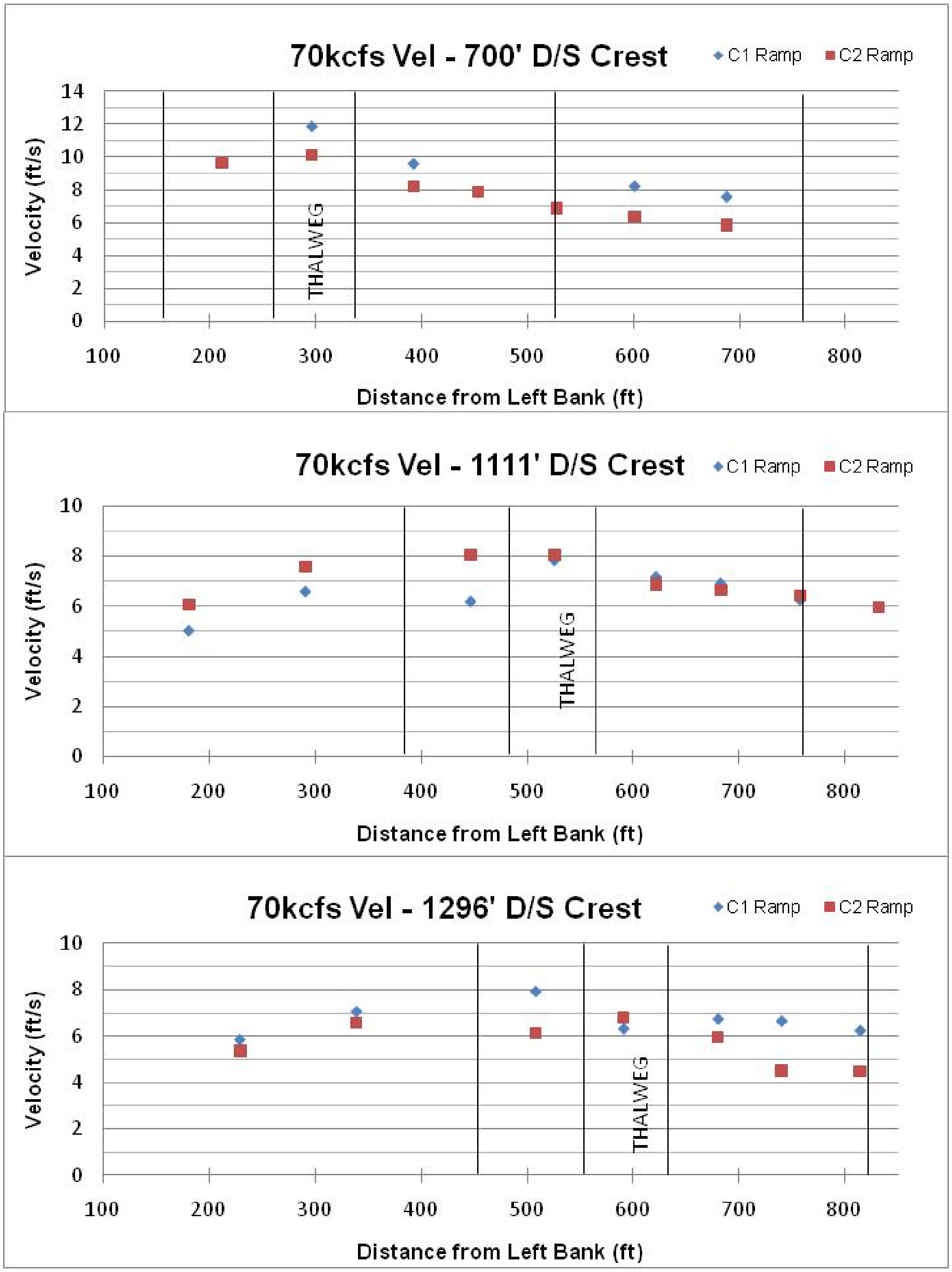


Figure 51. Comparison of original and modified ramp velocities of 70,000 ft^3/s at 700, 1111, and 1296 ft downstream of the crest.

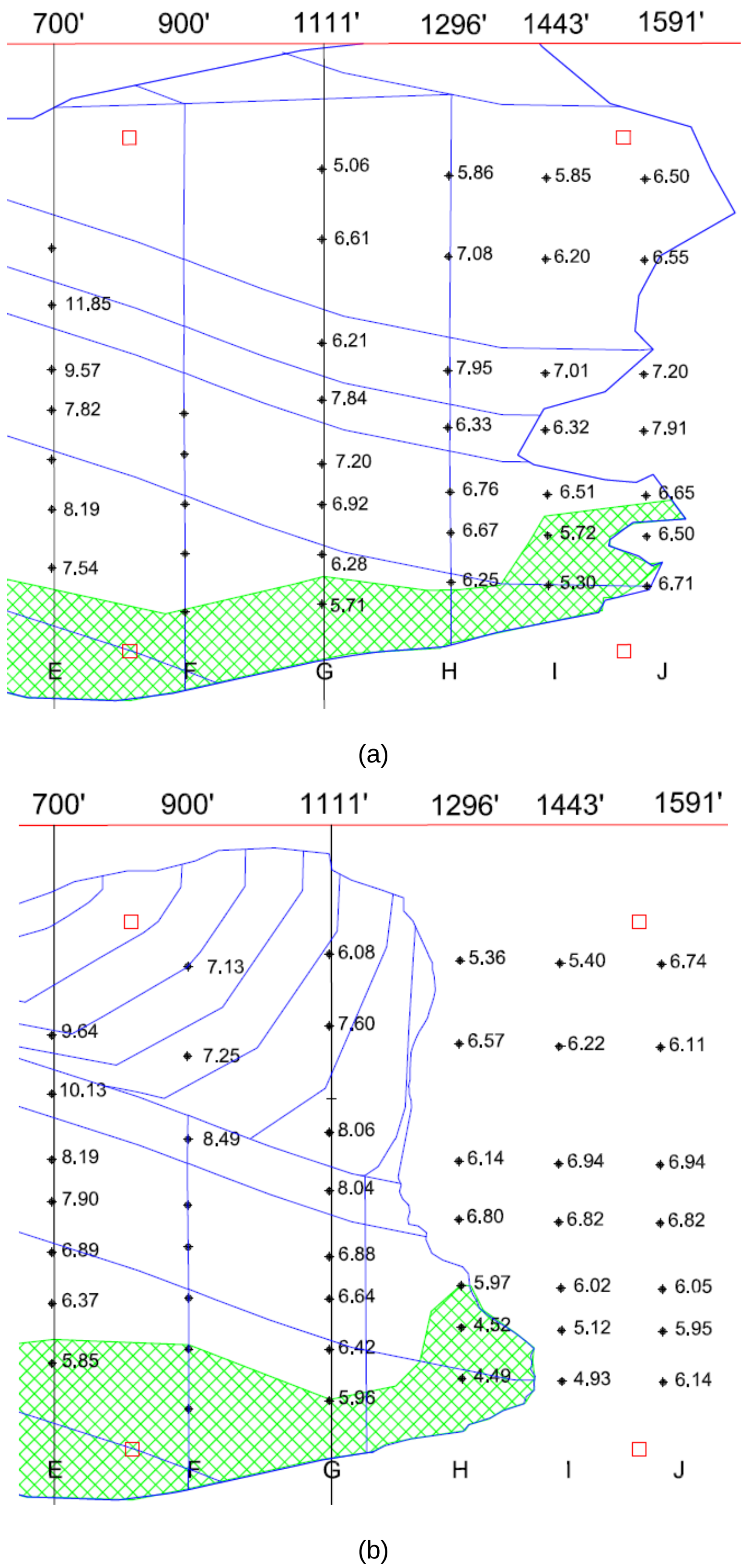


Figure 52. 70,000 ft^3/s velocity data from the C1 ramp (a) compared to the shortened C2 ramp (b); green hatch indicates areas on the ramp where velocity was less than 6 ft/s.

Steepened Toe Rock Ramp Discussion

At all river flows results showed that critical passage corridors with acceptable depths and velocities were not compromised by the shortened C2 ramp. Even though areas on the left side with acceptable velocities were reduced by the steepened slope, critical passage areas to the right were maintained. Increased velocities and depths in the area to the left of the thalweg indicated that more flow was drawn to that side of the ramp by the steepened slope. This was evident in river flows of 30,000 ft^3/s and greater. However, velocity decreased and depth increased near the ramp toe which was probably due to the increased drop of the bottom ramp surface and influence from the tailwater.

Effects from the tailwater were evident by the flow being dispersed across the ramp near the toe as indicated by velocity data. On the C1 ramp the flow was generally concentrated in the thalweg until near the ramp toe where velocities became more uniform across the width of the model. While the same was true for the C2 ramp, more flow was spread over the left side of the ramp. Also, lower velocity and greater depth near the toe of the C2 ramp suggest that the combination of the lower ramp surface and tailwater were the likely cause of the flow being dispersed. This was particularly seen in areas to the right of thalweg where the ramp was steepened to a 2% slope. As a result critical passage corridors with acceptable depths and velocities were preserved to the right of the thalweg.

The trends indicated by both velocity and depth are valuable in approximating the location of tailwater influence. Understanding where the downward flow from the ramp intersects the tailwater and how it affects velocities at the downstream ramp toe is critical in determining the limits for reducing ramp length. This point of tailwater intersection seemed to move upstream as river flow increased because of increasing tailwater elevation. While moving the intersection point upstream did not expand areas where velocities were in an acceptable range, it did seem to compensate for velocities that would otherwise be greater due to the increased flow coming down the ramp. This trend indicates that it may be possible for the ramp to be shortened by another 200 ft without affecting critical passage ways due to this influence from the tailwater. This could only be verified by addition testing in the physical model.

Conclusions and Recommendations

The Lower Yellowstone Diversion Weir and Rock Ramp design was tested in a 1:25 scale physical hydraulic model at Reclamation's laboratory facilities in Denver, CO. Results from both numerical and physical models were valuable in enhancing general understanding of design features and how they may affect hydraulic conditions necessary for irrigation diversion, fish passage, and ramp stability. Test results from the physical model were necessary in validating the design of the diversion weir and rock ramp and for forming the following conclusions and recommendations.

- Water surface elevation data showed that the proposed diversion weir provided sufficient upstream head to fully meet water district diversion objectives. Testing various ramp choking conditions helped confirm that future deposition of sediment within the ramp matrix will have no affect on the water district's ability to divert their full water right. The concrete weir caused a noticeable flow contraction over the crest. At the downstream edge, crest velocities were higher and depths were lower than predicted by the numerical simulations. While these issues have negligible effect on upstream diversion head, they are of concern for fish passage over the crest. Velocities measured in the physical model indicate velocities across much of the weir crest exceed the BRT maximum recommended passage velocity for pallid sturgeon.

- Testing the three different "choked" conditions were helpful in understanding how ramp hydraulics will likely be affected as ramp roughness may be reduced over time by sediment deposition. Results showed that choking the ramp surface decreased interstitial flow which increased depth and decreased velocity over the crest and immediately downstream. Choking the prototype rock ramp to at least ½ the diameter of the riprap is recommended.

  Further downstream relative surface roughness was reduced which caused velocity in areas to the right of the thalweg to increase significantly. While there were still passage corridors with acceptable depths and velocities near the right bank, these areas were reduced by increased velocities near midstream. Passage optimization features may be necessary to enlarge passage ways that meet BRT criteria.

- The boulder field labeled "Grid 6" provided the most improved flow conditions for fish passage. The width and boulder spacing of this configuration helped improve a critical passage way over the weir by reducing velocities at the crest and immediately downstream near the right bank. In general, depths were not significantly affected by the boulders. The shift of the downstream half of the boulder field toward the center of the ramp helped widen the passage corridor by forcing more of the flow into the thalweg and decreasing velocities downstream and towards the right bank.

Increased turbulence was observed from dye traces within the boulder field and immediately downstream. The impacts of relatively mild turbulence and shear zones on pallid sturgeon passage are of concern, although currently unknown. Despite these concerns, boulder fields improved flow conditions over the crest, provided a wider passage way with lower velocities, and provided a more diverse selection of flow paths over the ramp which is important for pallids and other fish species passing upstream.

- Data from depth and velocity measurements on the ramp and particularly near the toe confirm that the shortened version of the rock ramp (C2) should be utilized and will not negatively affect fish passage in excess of the C1 ramp design. The increased drop of the bottom ramp surface and influence from the tailwater resulted in greater depths and lower velocities near the toe. Critical passage areas at the approach to the ramp near the toe and along the right side of the ramp were not negatively affected by the steeper ramp slopes. Test results also showed that it may be possible for the ramp to be shortened even further due to effects from the tailwater. Additional testing in the physical model would be necessary for verification.

Overall, test results from the physical model confirm the concept and design of a diversion weir and rock ramp for passage of pallid sturgeon to the upstream river. Data confirmed that the diversion weir will provide adequate irrigation flow to the new canal headworks for all flow conditions tested. Test results also suggest that the rock ramp will provide a diverse selection of passage ways and areas with acceptable flow conditions as determined by BRT criteria for critical migration flows. Test data also indicate that the ramp's ability to divert water and provide fish passage will not be reduced as it changes over time.

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Appendices

Appendix A

Comparison of Physical and Numerical Thalweg Data – No Choke Condition

Yellow highlighted rows were plotted and represent the upstream water surface elevations (1-4), centerline measurements at the crest (6), mid upper ramp slope (13), mid second ramp slope (19), and mid bottom slope (25).

Initial ramp roughness with no choke material and larger rock material in the thalweg.

Table A- 1. Numerical and Physical data from No Choke condition at 7,000 cfs.

7 kcfs initial ramp		WS Elevation (ft)			Depth (ft)			Velocity (fps)		
Test Location	Elevation	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*
1	1979.44	1993.27	1992.49	1993.53	13.83	13.06	14.09	1.61		1.35
2	1978.95	1993.33	1992.62	1993.53	14.38	13.67	14.58	1.49		1.23
3	1979.07	1993.26	1992.74	1993.53	14.19	13.67	14.46	1.48		1.18
4	1978.90	1993.26	1992.57	1993.53	14.36	13.66	14.63	1.54		1.19
5	1989.38	1993.21		1993.48	3.84		4.11	3.73		2.65
6	1988.10	1993.11	1991.42	1993.45	5.13	3.32	5.47	4.16	6.78	3.04
7	1988.94	1993.10		1993.46	4.16		4.52	4.04		2.87
8	1989.35	1993.09		1993.46	3.74		4.10	3.90		2.72
9	1989.86	1993.14		1993.48	3.28		3.62	3.66		2.54
10	1991.02	1993.23		1993.51	2.21		2.49	2.45		1.63
11	1991.49	1993.26		1993.52	1.77		2.03	2.05		1.35
12	1989.03	1992.53		1992.83	3.50		3.80	4.52		2.94
13	1987.62	1992.45	1991.18	1992.79	4.83	3.61	5.17	5.50	4.02	3.88
14	1988.58	1992.38		1992.75	3.80		4.17	4.97		3.32
15	1989.50	1992.36		1992.74	2.86		3.23	4.20		2.69
16	1990.80	1992.38		1992.72	1.58		1.91	2.93		1.73
17	1991.21	1992.37		1992.69	1.16		1.48	2.32		1.36
18	1987.67	1990.96		1991.20	3.29		3.53	5.80		3.60
19	1986.33	1990.81	1989.02	1991.09	4.48	2.71	4.77	7.05	4.36	4.66
20	1987.32	1990.65		1990.97	3.33		3.65	5.80		3.74
21	1988.24	1990.57		1990.90	2.33		2.66	4.48		2.85
22	1989.51	1990.53		1990.83	1.01		1.31	2.51		1.49
23	1989.93	1990.57		1990.82	0.64		0.89	1.73		1.00
24	1985.66	1988.62		1988.84	2.97		3.19	6.93		4.12
25	1984.31	1988.44	1986.94	1988.70	4.13	2.68	4.38	8.42	4.07	5.34
26	1985.31	1988.30		1988.55	2.99		3.24	6.36		3.94
27	1986.22	1988.21		1988.46	1.99		2.24	4.48		2.75
28	1987.50	1988.09		1988.33	0.59		0.83	1.71		1.00
29	1988.95	1988.11		1988.37	-0.85		-0.59	0.45		0.26
TailWater			1985.79							

Table A- 2. Numerical and Physical data from No Choke condition at 15,000 cfs.

15 kcfs initial ramp		WS Elevation (ft)			Depth (ft)			Velocity (fps)		
Test Location	Elevation	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*
1	1979.44	1994.52	1994.23	1995.49	15.08	14.80	16.05	2.64		2.42
2	1978.95	1994.53	1994.34	1995.50	15.58	15.39	16.55	2.46		2.26
3	1979.07	1994.52	1994.44	1995.49	15.46	15.37	16.42	2.44		2.23
4	1978.90	1994.52	1994.19	1995.49	15.62	15.29	16.59	2.48		2.23
5	1989.38	1994.29		1995.36	4.91	3.83	5.99	5.01		4.05
6	1987.97	1994.22	1993.10	1995.31	6.25	5.00	7.33	5.46	6.99	4.43
7	1988.94	1994.23		1995.31	5.29	4.00	6.37	5.29	7.85	4.28
8	1989.35	1994.21		1995.31	4.86	4.23	5.96	5.17		4.15
9	1989.86	1994.26		1995.33	4.40	2.87	5.47	4.97	8.34	4.02
10	1991.02	1994.34		1995.37	3.32	2.22	4.35	3.88	6.18	3.23
11	1991.49	1994.37		1995.38	2.87		3.88	3.50		2.98
12	1989.03	1993.48		1994.58	4.45		5.55	5.80		4.44
13	1987.62	1993.45	1992.58	1994.55	5.83	4.97	6.93	6.62	6.51	5.23
14	1988.58	1993.41		1994.50	4.82		5.92	6.19		4.80
15	1989.50	1993.38		1994.48	3.88		4.98	5.59		4.27
16	1990.80	1993.36		1994.42	2.55		3.62	4.55		3.45
17	1991.21	1993.31		1994.35	2.10		3.14	4.06		3.12
18	1987.67	1991.75		1992.72	4.09		5.05	7.25		5.31
19	1986.33	1991.64	1990.91	1992.63	5.32	4.59	6.31	8.23	5.49	6.14
20	1987.32	1991.49		1992.52	4.17	3.32	5.19	7.03	3.83	5.24
21	1988.24	1991.42		1992.46	3.18	2.52	4.22	5.84	3.54	4.43
22	1989.51	1991.35		1992.39	1.84	1.23	2.88	4.19	2.36	3.27
23	1989.93	1991.35		1992.38	1.42		2.45	3.43		2.81
24	1985.66	1989.31		1990.28	3.66		4.62	8.46		5.90
25	1984.31	1989.18	1988.90	1990.17	4.87	4.51	5.86	9.48	6.70	6.76
26	1985.31	1989.06		1990.07	3.75		4.76	7.41		5.39
27	1986.22	1988.97		1990.01	2.75		3.78	5.67		4.33
28	1987.50	1988.85		1989.97	1.34		2.47	3.35		3.03
29	1988.95	1988.86		1990.02	-0.09		1.06	0.90		1.08
TailWater			1987.93							

Table A- 3. Numerical and Physical data from No Choke condition at 30,000 cfs.

30 kcfs initial ramp		**WS Elevation (ft)**			**Depth (ft)**			**Velocity (fps)**		
Test Location	Elevation	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*
1	1979.44	1996.61	1996.50	1997.75	17.18	17.06	18.31	4.25		3.86
2	1978.95	1996.68	1996.62	1997.76	17.73	17.67	18.81	4.03		3.66
3	1979.07	1996.60	1996.59	1997.75	17.54	17.52	18.69	4.01		3.63
4	1978.90	1996.59	1996.54	1997.75	17.69	17.64	18.85	4.01		3.62
5	1989.38	1996.14		1997.43	6.77	6.23	8.06	7.28		5.94
6	1988.10	1996.11	1995.00	1997.49	8.01	6.92	9.39	7.72	8.30	6.31
7	1988.94	1995.96		1997.36	7.02	5.86	8.42	7.52	8.58	6.12
8	1989.35	1995.95		1997.36	6.60	6.08	8.01	7.44		6.02
9	1989.86	1995.99		1997.37	6.13	4.96	7.51	7.26	8.06	5.91
10	1991.02	1996.09		1997.41	5.08	3.87	6.40	6.11	7.48	4.98
11	1991.49	1996.18		1997.44	4.69	3.49	5.95	5.56	7.35	4.64
12	1989.03	1995.21		1996.54	6.18		7.51	8.01		6.23
13	1987.62	1995.11	1994.38	1996.50	7.49	6.82	8.88	8.60	8.16	6.89
14	1988.58	1995.03		1996.45	6.45		7.86	8.25		6.52
15	1989.50	1995.01		1996.42	5.50		6.91	7.81		6.08
16	1990.80	1994.95		1996.33	4.15		5.52	7.00		5.36
17	1991.21	1994.85		1996.22	3.63		5.01	6.65		5.10
18	1987.67	1993.20		1994.42	5.53		6.75	9.54		7.20
19	1986.33	1993.09	1993.01	1994.36	6.77	6.71	8.04	10.10	7.87	7.76
20	1987.32	1992.97		1994.27	5.65	5.38	6.95	9.02	5.86	6.86
21	1988.24	1992.91		1994.22	4.67	4.63	5.98	8.01	5.74	6.09
22	1989.51	1992.89		1994.19	3.37	3.40	4.67	6.73	4.14	5.08
23	1989.93	1992.89		1994.18	2.96	2.57	4.25	6.15	2.69	4.67
24	1985.66	1990.91		1992.04	5.25		6.39	10.53		7.65
25	1984.31	1990.87	1991.50	1992.00	6.55	7.26	7.69	10.47	7.38	7.95
26	1985.31	1990.84		1991.95	5.53		6.65	8.32		6.61
27	1986.22	1990.82		1991.93	4.60		5.70	7.03		5.74
28	1987.50	1990.79		1991.94	3.29		4.44	5.82		4.92
29	1988.95	1990.74		1991.98	1.79		3.03	1.61		2.82
TailWater			1990.69							

Table A- 4. Numerical and Physical data from No Choke condition at 40,000 cfs.

40 kcfs initial ramp		**WS Elevation (ft)**			**Depth (ft)**			**Velocity (fps)**		
Test Location	Elevation	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*
1	1979.44	1999.11	1997.70	1998.90	19.68	18.26	19.46	4.83		4.64
2	1978.95	1999.18	1997.82	1998.91	20.23	18.87	19.96	4.62		4.42
3	1979.07	1999.10	1997.82	1998.90	20.03	18.75	19.83	4.59		4.39
4	1978.90	1999.09	1997.62	1998.90	20.19	18.71	20.00	4.49		4.36
5	1989.38	1998.75		1998.49	9.38	7.21	9.12	7.13		6.88
6	1987.97	1998.63	1996.20	1998.44	10.66	8.10	10.47	7.37	8.98	7.18
7	1988.94	1998.58		1998.42	9.64	6.97	9.49	7.23	9.21	6.98
8	1989.35	1998.59		1998.41	9.23	7.92	9.06	7.06		6.89
9	1989.86	1998.59		1998.41	8.73	5.97	8.55	7.04	9.06	6.89
10	1991.02	1998.67		1998.48	7.65	4.99	7.46	5.94	7.64	5.75
11	1991.49	1998.68		1998.48	7.18	4.53	6.99	5.55	7.70	5.41
12	1989.03	1997.76		1997.52	8.73		8.49	7.38		7.17
13	1987.62	1997.67	1995.44	1997.48	10.04	7.87	9.85	7.90	8.90	7.75
14	1988.58	1997.58		1997.42	9.00		8.83	7.58		7.41
15	1989.50	1997.55		1997.38	8.04		7.88	7.18		7.01
16	1990.80	1997.45		1997.28	6.65		6.47	6.51		6.32
17	1991.21	1997.32		1997.16	6.11		5.95	6.28		6.08
18	1987.67	1995.49		1995.29	7.83		7.62	8.32		8.11
19	1986.33	1995.43	1994.21	1995.25	9.11	7.90	8.93	8.69	8.32	8.54
20	1987.32	1995.35		1995.18	8.03	6.69	7.85	7.74	5.75	7.63
21	1988.24	1995.32		1995.14	7.08	5.95	6.90	7.00	5.99	6.88
22	1989.51	1995.32		1995.13	5.80	4.74	5.61	6.03	5.06	5.90
23	1989.93	1995.32		1995.13	5.39	3.90	5.20	5.63	3.98	5.50
24	1985.66	1993.36		1993.07	7.70		7.41	8.42		8.30
25	1984.31	1993.32	1992.86	1993.06	9.01	8.60	8.75	8.31	6.84	8.32
26	1985.31	1993.29		1993.04	7.98		7.73	7.01		7.03
27	1986.22	1993.28		1993.03	7.06		6.80	6.29		6.28
28	1987.50	1993.31		1993.05	5.81		5.55	5.77		5.68
29	1988.95	1993.28		1993.07	4.33		4.12	3.75		3.71
TailWater			1992.23							

Table A- 5. Numerical and Physical data from No Choke condition at 70,000 cfs.

70 kcfs intial ramp		WS Elevation (ft)			Depth (ft)			Velocity (fps)		
Test Location	Elevation	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*
1	1979.44	2002.15	2000.78	2002.10	22.71	21.34	22.66	6.89		6.81
2	1978.95	2002.22	2000.64	2002.14	23.27	21.69	23.19	6.66		6.60
3	1979.07	2002.13	2000.67	2002.14	23.07	21.60	23.08	6.62		6.58
4	1978.90	2002.13	2000.59	2002.16	23.23	21.69	23.25	6.47		6.50
5	1989.38	2001.55		2001.50	12.17	9.21	12.13	9.46		9.42
6	1987.97	2001.36	1998.93	2001.38	13.39	10.83	13.40	9.80	10.39	9.82
7	1988.94	2001.32		2001.34	12.38	9.71	12.40	9.56	10.50	9.57
8	1989.35	2001.30		2001.33	11.95	10.36	11.98	9.45		9.45
9	1989.86	2001.31		2001.34	11.45	8.68	11.47	9.27	10.68	9.28
10	1991.02	2001.40		2001.42	10.38	7.69	10.40	7.95	8.47	7.94
11	1991.49	2001.40		2001.41	9.91	7.22	9.91	7.44	8.55	7.46
12	1989.03	2000.36		2000.32	11.33		11.29	9.79		9.77
13	1987.62	2000.25	1997.92	2000.25	12.63	10.35	12.63	10.19	8.84	10.18
14	1988.58	2000.14		2000.17	11.56		11.59	9.87		9.88
15	1989.50	2000.10		2000.12	10.60		10.62	9.50		9.52
16	1990.80	1999.97		1999.98	9.17		9.17	8.86		8.86
17	1991.21	1999.81		1999.83	8.59		8.62	8.69		8.69
18	1987.67	1997.94		1997.90	10.27		10.23	10.46		10.45
19	1986.33	1997.95	1997.04	1997.95	11.63	10.73	11.63	10.49	8.59	10.50
20	1987.32	1997.94		1997.95	10.62	9.62	10.63	9.51	8.10	9.52
21	1988.24	1997.95		1997.95	9.71	8.89	9.71	8.78	7.53	8.79
22	1989.51	1998.01		1998.02	8.50	7.72	8.50	7.75	6.21	7.75
23	1989.93	1998.06		1998.06	8.13	6.90	8.13	7.28	5.68	7.29
24	1985.66	1996.45		1996.41	10.79		10.75	9.49		9.48
25	1984.31	1996.46	1996.10	1996.46	12.15	11.84	12.15	8.93	7.55	8.95
26	1985.31	1996.47		1996.48	11.17		11.18	7.87		7.89
27	1986.22	1996.49		1996.49	10.26		10.27	7.46		7.47
28	1987.50	1996.53		1996.53	9.03		9.03	7.28		7.28
29	1988.95	1996.46		1996.52	7.51		7.56	5.78		5.76
TailWater			1995.69							

Comparison of Physical and Numerical Thalweg Data – Mid Choke Condition

Yellow highlighted rows were plotted and represent the upstream water surface elevation (1), centerline measurements at the crest (6), mid upper ramp slope (13), mid second ramp slope (19), and mid bottom slope (25).

Half choked ramp roughness with the entire ramp choked including the larger material in the thalweg.

Table A- 6. Numerical and Physical data from Mid Choke condition at 7,000 cfs.

7kcfs - half choke		WS Elevation (ft)			Depth (ft)			Velocity (fps)		
Test Location	Elevation	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*
1	1979.44	1993.27	1992.83	1993.53	13.83	13.39	14.09	1.61		1.35
2	1978.95	1993.33		1993.53	14.38		14.58	1.49		1.23
3	1979.07	1993.26		1993.53	14.19		14.46	1.48		1.18
4	1978.90	1993.26		1993.53	14.36		14.63	1.54		1.19
5	1989.38	1993.21		1993.48	3.84		4.11	3.73		2.65
6	1988.10	1993.11	1992.20	1993.45	5.13	4.10	5.47	4.16	4.97	3.04
7	1988.94	1993.10		1993.46	4.16		4.52	4.04		2.87
8	1989.35	1993.09		1993.46	3.74		4.10	3.90		2.72
9	1989.86	1993.14		1993.48	3.28		3.62	3.66		2.54
10	1991.02	1993.23		1993.51	2.21		2.49	2.45		1.63
11	1991.49	1993.26		1993.52	1.77		2.03	2.05		1.35
12	1989.03	1992.53		1992.83	3.50		3.80	4.52		2.94
13	1987.62	1992.45	1991.28	1992.79	4.83	3.71	5.17	5.50	4.46	3.88
14	1988.58	1992.38		1992.75	3.80		4.17	4.97		3.32
15	1989.50	1992.36		1992.74	2.86		3.23	4.20		2.69
16	1990.80	1992.38		1992.72	1.58		1.91	2.93		1.73
17	1991.21	1992.37		1992.69	1.16		1.48	2.32		1.36
18	1987.67	1990.96		1991.20	3.29		3.53	5.80		3.60
19	1986.33	1990.81	1989.61	1991.09	4.48	3.30	4.77	7.05	5.09	4.66
20	1987.32	1990.65		1990.97	3.33		3.65	5.80		3.74
21	1988.24	1990.57		1990.90	2.33		2.66	4.48		2.85
22	1989.51	1990.53		1990.83	1.01		1.31	2.51		1.49
23	1989.93	1990.57		1990.82	0.64		0.89	1.73		1.00
24	1985.66	1988.62		1988.84	2.97		3.19	6.93		4.12
25	1984.31	1988.44	1987.11	1988.70	4.13	2.85	4.38	8.42	4.39	5.34
26	1985.31	1988.30		1988.55	2.99		3.24	6.36		3.94
27	1986.22	1988.21		1988.46	1.99		2.24	4.48		2.75
28	1987.50	1988.09		1988.33	0.59		0.83	1.71		1.00
29	1988.95	1988.11		1988.37	-0.85		-0.59	0.45		0.26
TailWater			1985.46							

Table A- 7. Numerical and Physical data from Mid Choke condition at 15,000 cfs.

15 kcfs half choke		WS Elevation (ft)			Depth (ft)			Velocity (fps)		
Test Location	Elevation	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*
1	1979.44	1994.52	1994.54	1995.49	15.08	15.10	16.05	2.64		2.42
2	1978.95	1994.53		1995.50	15.58		16.55	2.46		2.26
3	1979.07	1994.52		1995.49	15.46		16.42	2.44		2.23
4	1978.90	1994.52		1995.49	15.62		16.59	2.48		2.23
5	1989.38	1994.29		1995.36	4.91		5.99	5.01		4.05
6	1987.97	1994.22	1993.68	1995.31	6.25	5.58	7.33	5.46	6.32	4.43
7	1988.94	1994.23		1995.31	5.29	4.77	6.37	5.29	6.60	4.28
8	1989.35	1994.21		1995.31	4.86		5.96	5.17		4.15
9	1989.86	1994.26		1995.33	4.40	4.05	5.47	4.97	5.88	4.02
10	1991.02	1994.34		1995.37	3.32	2.47	4.35	3.88	6.11	3.23
11	1991.49	1994.37		1995.38	2.87		3.88	3.50		2.98
12	1989.03	1993.48		1994.58	4.45		5.55	5.80		4.44
13	1987.62	1993.45	1992.54	1994.55	5.83	4.97	6.93	6.62	6.98	5.23
14	1988.58	1993.41		1994.50	4.82		5.92	6.19		4.80
15	1989.50	1993.38		1994.48	3.88		4.98	5.59		4.27
16	1990.80	1993.36		1994.42	2.55		3.62	4.55		3.45
17	1991.21	1993.31		1994.35	2.10		3.14	4.06		3.12
18	1987.67	1991.75		1992.72	4.09		5.05	7.25		5.31
19	1986.33	1991.64	1991.03	1992.63	5.32	4.72	6.31	8.23	6.67	6.14
20	1987.32	1991.49		1992.52	4.17	3.67	5.19	7.03	6.28	5.24
21	1988.24	1991.42		1992.46	3.18	2.65	4.22	5.84	4.06	4.43
22	1989.51	1991.35		1992.39	1.84	1.34	2.88	4.19	3.28	3.27
23	1989.93	1991.35		1992.38	1.42		2.45	3.43		2.81
24	1985.66	1989.31		1990.28	3.66		4.62	8.46		5.90
25	1984.31	1989.18	1988.94	1990.17	4.87	4.68	5.86	9.48	7.95	6.76
26	1985.31	1989.06		1990.07	3.75		4.76	7.41		5.39
27	1986.22	1988.97		1990.01	2.75		3.78	5.67		4.33
28	1987.50	1988.85		1989.97	1.34		2.47	3.35		3.03
29	1988.95	1988.86		1990.02	-0.09		1.06	0.90		1.08
TailWater			1987.63							

Table A- 8. Numerical and Physical data from Mid Choke condition at 30,000 cfs.

30 kcfs half choke		WS Elevation (ft)			Depth (ft)			Velocity (fps)		
Test Location	Elevation	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*
1	1979.44	1996.61	1996.66	1997.75	17.18	17.22	18.31	4.25		3.86
2	1978.95	1996.68		1997.76	17.73		18.81	4.03		3.66
3	1979.07	1996.60		1997.75	17.54		18.69	4.01		3.63
4	1978.90	1996.59		1997.75	17.69		18.85	4.01		3.62
5	1989.38	1996.14		1997.43	6.77		8.06	7.28		5.94
6	1988.10	1996.11	1995.42	1997.49	8.01	7.32	9.39	7.72	7.73	6.31
7	1988.94	1995.96	1995.47	1997.36	7.02	6.45	8.42	7.52	7.85	6.12
8	1989.35	1995.95		1997.36	6.60		8.01	7.44		6.02
9	1989.86	1995.99	n	1997.37	6.13		7.51	7.26		5.91
10	1991.02	1996.09	1995.58	1997.41	5.08	4.31	6.40	6.11	6.76	4.98
11	1991.49	1996.18	1995.35	1997.44	4.69	3.67	5.95	5.56	6.93	4.64
12	1989.03	1995.21		1996.54	6.18		7.51	8.01		6.23
13	1987.62	1995.11	1994.43	1996.50	7.49	6.86	8.88	8.60	8.07	6.89
14	1988.58	1995.03		1996.45	6.45		7.86	8.25		6.52
15	1989.50	1995.01		1996.42	5.50		6.91	7.81		6.08
16	1990.80	1994.95		1996.33	4.15		5.52	7.00		5.36
17	1991.21	1994.85		1996.22	3.63		5.01	6.65		5.10
18	1987.67	1993.20		1994.42	5.53		6.75	9.54		7.20
19	1986.33	1993.09	1992.89	1994.36	6.77	6.58	8.04	10.10	8.71	7.76
20	1987.32	1992.97	1992.76	1994.27	5.65	5.54	6.95	9.02	6.81	6.86
21	1988.24	1992.91	n	1994.22	4.67		5.98	8.01		6.09
22	1989.51	1992.89	1992.80	1994.19	3.37	3.33	4.67	6.73	4.61	5.08
23	1989.93	1992.89	1992.82	1994.18	2.96	2.94	4.25	6.15	3.42	4.67
24	1985.66	1990.91		1992.04	5.25		6.39	10.53		7.65
25	1984.31	1990.87	1991.15	1992.00	6.55	6.89	7.69	10.47	7.57	7.95
26	1985.31	1990.84		1991.95	5.53		6.65	8.32		6.61
27	1986.22	1990.82		1991.93	4.60		5.70	7.03		5.74
28	1987.50	1990.79		1991.94	3.29		4.44	5.82		4.92
29	1988.95	1990.74		1991.98	1.79		3.03	1.61		2.82
TailWater			1990.39							

Table A- 9. Numerical and Physical data from Mid Choke condition at 40,000 cfs.

40 kcfs half choke		WS Elevation (ft)			Depth (ft)			Velocity (fps)		
Test Location	Elevation	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*
1	1979.44	1997.65	1997.93	1998.90	18.2	18.49	19.5	5.1		4.6
2	1978.95	1997.72		1998.91	18.8		20.0	4.9		4.4
3	1979.07	1997.64		1998.90	18.6		19.8	4.9		4.4
4	1978.90	1997.62		1998.90	18.7		20.0	4.8		4.4
5	1989.38	1997.05		1998.49	7.7		9.1	8.4		6.9
6	1987.97	1996.85	1996.51	1998.44	8.9	8.41	10.5	8.8	8.16	7.2
7	1988.94	1996.83	1996.48	1998.42	7.9	7.46	9.5	8.5	8.65	7.0
8	1989.35	1996.81		1998.41	7.5		9.1	8.5		6.9
9	1989.86	1996.85	1996.47	1998.41	7.0	6.54	8.5	8.3	8.34	6.9
10	1991.02	1997.02	1996.61	1998.48	6.0	5.34	7.5	6.9	7.30	5.8
11	1991.49	1997.05	1996.39	1998.48	5.6	4.71	7.0	6.4	7.42	5.4
12	1989.03	1995.99		1997.52	7.0		8.5	9.1		7.2
13	1987.62	1995.89	1995.11	1997.48	8.3	7.54	9.9	9.6	9.26	7.8
14	1988.58	1995.80		1997.42	7.2		8.8	9.3		7.4
15	1989.50	1995.77		1997.38	6.3		7.9	8.9		7.0
16	1990.80	1995.69		1997.28	4.9		6.5	8.2		6.3
17	1991.21	1995.56		1997.16	4.4		5.9	7.9		6.1
18	1987.67	1993.85		1995.29	6.2		7.6	10.6		8.1
19	1986.33	1993.78	1993.90	1995.25	7.5	7.59	8.9	11.0	9.54	8.5
20	1987.32	1993.67	1993.88	1995.18	6.4	6.66	7.9	9.9	7.77	7.6
21	1988.24	1993.63	1993.88	1995.14	5.4	5.74	6.9	9.0	6.88	6.9
22	1989.51	1993.63	1993.96	1995.13	4.1	4.49	5.6	7.7	5.49	5.9
23	1989.93	1993.65	1993.99	1995.13	3.7	4.11	5.2	7.2	4.81	5.5
24	1985.66	1991.93		1993.07	6.3		7.4	10.8		8.3
25	1984.31	1991.96	1992.61	1993.06	7.7	8.35	8.8	10.3	7.39	8.3
26	1985.31	1991.98		1993.04	6.7		7.7	8.3		7.0
27	1986.22	1991.97		1993.03	5.8		6.8	7.2		6.3
28	1987.50	1991.97		1993.05	4.5		5.5	6.4		5.7
29	1988.95	1991.92		1993.07	3.0		4.1	2.0		3.7
TailWater			1992.05							

Table A- 10. Numerical and Physical data from Mid Choke condition at 70,000 cfs.

70 kcfs half choke		WS Elevation (ft)			Depth (ft)			Velocity (fps)		
Test Location	Elevation	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*
1	1979.44	2000.42	2000.86	2002.10	21.0	21.42	22.7	7.3		6.8
2	1978.95	2000.49		2002.14	21.5		23.2	7.0		6.60
3	1979.07	2000.40		2002.14	21.3		23.1	7.0		6.58
4	1978.90	2000.38		2002.16	21.5		23.3	6.8		6.50
5	1989.38	1999.47		2001.50	10.1		12.1	10.9		9.42
6	1987.97	1999.23	1999.08	2001.38	11.3	10.98	13.4	11.3	9.51	9.82
7	1988.94	1999.18	1999.04	2001.34	10.2	10.02	12.4	11.1	9.95	9.57
8	1989.35	1999.14		2001.33	9.8		12.0	11.0		9.45
9	1989.86	1999.20	1998.95	2001.34	9.3	9.02	11.5	10.7	10.10	9.28
10	1991.02	1999.33	1999.23	2001.42	8.3	7.96	10.4	9.2	7.97	7.94
11	1991.49	1999.42	1999.01	2001.41	7.9	7.33	9.9	8.4	8.37	7.46
12	1989.03	1998.12		2000.32	9.1		11.3	11.9		9.77
13	1987.62	1997.99	1997.71	2000.25	10.4	10.14	12.6	12.2	10.74	10.18
14	1988.58	1997.87		2000.17	9.3		11.6	11.9		9.88
15	1989.50	1997.82		2000.12	8.3		10.6	11.6		9.52
16	1990.80	1997.65		1999.98	6.9		9.2	11.0		8.86
17	1991.21	1997.46		1999.83	6.3		8.6	10.8		8.69
18	1987.67	1995.88		1997.90	8.2		10.2	12.9		10.45
19	1986.33	1995.93	1996.68	1997.95	9.6	10.37	11.6	12.8	10.18	10.50
20	1987.32	1995.94	1996.63	1997.95	8.6	9.41	10.6	11.6	8.85	9.52
21	1988.24	1995.97	1996.68	1997.95	7.7	8.54	9.7	10.7	7.65	8.79
22	1989.51	1996.09	1996.82	1998.02	6.6	7.35	8.5	9.3	6.98	7.75
23	1989.93	1996.18	1996.88	1998.06	6.3	7.00	8.1	8.6	6.55	7.29
24	1985.66	1995.30		1996.41	9.6		10.8	10.9		9.48
25	1984.31	1995.35	1995.85	1996.46	11.0	11.59	12.2	9.8	8.37	8.95
26	1985.31	1995.40		1996.48	10.1		11.2	8.3		7.89
27	1986.22	1995.41		1996.49	9.2		10.3	7.8		7.47
28	1987.50	1995.44		1996.53	7.9		9.0	7.5		7.28
29	1988.95	1995.38		1996.52	6.4		7.6	3.6		5.76
TailWater			1995.42							

Comparison of Physical and Numerical Thalweg Data – Full Choke Condition

Yellow highlighted rows were plotted and represent the upstream water surface elevation (1), centerline measurements at the crest (6), mid upper ramp slope (13), mid second ramp slope (19), and mid bottom slope (25).

Fully choked ramp roughness with the side slopes fully choked and the thalweg left at half choked condition.

Table A- 11. Numerical and Physical data from Full Choke condition at 7,000 cfs.

7 kcfs fully choked		WS Elevation (ft)			Depth (ft)			Velocity (fps)		
Test Location	Elevation	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*
1	1979.44	1993.27	1992.82	1993.53	13.83	13.38	14.09	1.61		1.35
2	1978.95	1993.33		1993.53	14.38		14.58	1.49		1.23
3	1979.07	1993.26		1993.53	14.19		14.46	1.48		1.18
4	1978.90	1993.26		1993.53	14.36		14.63	1.54		1.19
5	1989.38	1993.21		1993.48	3.84		4.11	3.73		2.65
6	1988.10	1993.11	1992.27	1993.45	5.13	4.17	5.47	4.16	5.09	3.04
7	1988.94	1993.10		1993.46	4.16		4.52	4.04		2.87
8	1989.35	1993.09		1993.46	3.74		4.10	3.90		2.72
9	1989.86	1993.14		1993.48	3.28		3.62	3.66		2.54
10	1991.02	1993.23		1993.51	2.21		2.49	2.45		1.63
11	1991.49	1993.26		1993.52	1.77		2.03	2.05		1.35
12	1989.03	1992.53		1992.83	3.50		3.80	4.52		2.94
13	1987.62	1992.45	1991.45	1992.79	4.83	3.88	5.17	5.50	5.50	3.88
14	1988.58	1992.38		1992.75	3.80		4.17	4.97		3.32
15	1989.50	1992.36		1992.74	2.86		3.23	4.20		2.69
16	1990.80	1992.38		1992.72	1.58		1.91	2.93		1.73
17	1991.21	1992.37		1992.69	1.16		1.48	2.32		1.36
18	1987.67	1990.96		1991.20	3.29		3.53	5.80		3.60
19	1986.33	1990.81	1989.79	1991.09	4.48	3.48	4.77	7.05	4.48	4.66
20	1987.32	1990.65		1990.97	3.33		3.65	5.80		3.74
21	1988.24	1990.57		1990.90	2.33		2.66	4.48		2.85
22	1989.51	1990.53		1990.83	1.01		1.31	2.51		1.49
23	1989.93	1990.57		1990.82	0.64		0.89	1.73		1.00
24	1985.66	1988.62		1988.84	2.97		3.19	6.93		4.12
25	1984.31	1988.44	1987.23	1988.70	4.13	2.97	4.38	8.42	5.72	5.34
26	1985.31	1988.30		1988.55	2.99		3.24	6.36		3.94
27	1986.22	1988.21		1988.46	1.99		2.24	4.48		2.75
28	1987.50	1988.09		1988.33	0.59		0.83	1.71		1.00
29	1988.95	1988.11		1988.37	-0.85		-0.59	0.45		0.26
TailWater			1985.28							

Table A- 12. Numerical and Physical data from Full Choke condition at 15,000 cfs.

15 kcfs fully choked		**WS Elevation (ft)**			**Depth (ft)**			**Velocity (fps)**		
Test Location	Elevation	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*
1	1979.44	1994.52	1994.50	1995.49	15.08	15.07	16.05	2.64		2.42
2	1978.95	1994.53		1995.50	15.58		16.55	2.46		2.26
3	1979.07	1994.52		1995.49	15.46		16.42	2.44		2.23
4	1978.90	1994.52		1995.49	15.62		16.59	2.48		2.23
5	1989.38	1994.29		1995.36	4.91		5.99	5.01		4.05
6	1987.97	1994.22	1993.79	1995.31	6.25	5.69	7.33	5.46	6.01	4.43
7	1988.94	1994.23		1995.31	5.29	5.00	6.37	5.29	6.36	4.28
8	1989.35	1994.21		1995.31	4.86		5.96	5.17		4.15
9	1989.86	1994.26		1995.33	4.40	4.22	5.47	4.97	5.91	4.02
10	1991.02	1994.34		1995.37	3.32	2.75	4.35	3.88	5.40	3.23
11	1991.49	1994.37		1995.38	2.87		3.88	3.50		2.98
12	1989.03	1993.48		1994.58	4.45		5.55	5.80		4.44
13	1987.62	1993.45	1992.78	1994.55	5.83	5.21	6.93	6.62	7.78	5.23
14	1988.58	1993.41		1994.50	4.82		5.92	6.19		4.80
15	1989.50	1993.38		1994.48	3.88		4.98	5.59		4.27
16	1990.80	1993.36		1994.42	2.55		3.62	4.55		3.45
17	1991.21	1993.31		1994.35	2.10		3.14	4.06		3.12
18	1987.67	1991.75		1992.72	4.09		5.05	7.25		5.31
19	1986.33	1991.64	1991.22	1992.63	5.32	4.91	6.31	8.23	7.34	6.14
20	1987.32	1991.49		1992.52	4.17	3.78	5.19	7.03	6.72	5.24
21	1988.24	1991.42		1992.46	3.18	2.75	4.22	5.84	5.55	4.43
22	1989.51	1991.35		1992.39	1.84	1.35	2.88	4.19	2.22	3.27
23	1989.93	1991.35		1992.38	1.42		2.45	3.43		2.81
24	1985.66	1989.31		1990.28	3.66		4.62	8.46		5.90
25	1984.31	1989.18	1989.08	1990.17	4.87	4.82	5.86	9.48	7.20	6.76
26	1985.31	1989.06		1990.07	3.75		4.76	7.41		5.39
27	1986.22	1988.97		1990.01	2.75		3.78	5.67		4.33
28	1987.50	1988.85		1989.97	1.34		2.47	3.35		3.03
29	1988.95	1988.86		1990.02	-0.09		1.06	0.90		1.08
TailWater			1987.65							

Table A- 13. Numerical and Physical data from Full Choke condition at 30,000 cfs.

30 kcfs full choke		**WS Elevation (ft)**			**Depth (ft)**			**Velocity (fps)**		
Test Location	Elevation	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*
1	1979.44	1996.61	1996.67	1997.75	17.18	17.23	18.31	4.25		3.86
2	1978.95	1996.68		1997.76	17.73		18.81	4.03		3.66
3	1979.07	1996.60		1997.75	17.54		18.69	4.01		3.63
4	1978.90	1996.59		1997.75	17.69		18.85	4.01		3.62
5	1989.38	1996.14		1997.43	6.77		8.06	7.28		5.94
6	1988.10	1996.11	1995.52	1997.49	8.01	7.42	9.39	7.72	8.00	6.31
7	1988.94	1995.96	1995.71	1997.36	7.02	6.69	8.42	7.52	8.04	6.12
8	1989.35	1995.95		1997.36	6.60		8.01	7.44		6.02
9	1989.86	1995.99	1995.78	1997.37	6.13	5.85	7.51	7.26	7.38	5.91
10	1991.02	1996.09	1995.70	1997.41	5.08	4.43	6.40	6.11	6.82	4.98
11	1991.49	1996.18	1995.76	1997.44	4.69	4.08	5.95	5.56	6.41	4.64
12	1989.03	1995.21		1996.54	6.18		7.51	8.01		6.23
13	1987.62	1995.11	1994.44	1996.50	7.49	6.87	8.88	8.60	9.04	6.89
14	1988.58	1995.03		1996.45	6.45		7.86	8.25		6.52
15	1989.50	1995.01		1996.42	5.50		6.91	7.81		6.08
16	1990.80	1994.95		1996.33	4.15		5.52	7.00		5.36
17	1991.21	1994.85		1996.22	3.63		5.01	6.65		5.10
18	1987.67	1993.20		1994.42	5.53		6.75	9.54		7.20
19	1986.33	1993.09	1992.86	1994.36	6.77	6.55	8.04	10.10	8.68	7.76
20	1987.32	1992.97	1992.67	1994.27	5.65	5.45	6.95	9.02	8.74	6.86
21	1988.24	1992.91	1992.65	1994.22	4.67	4.51	5.98	8.01	7.90	6.09
22	1989.51	1992.89	1992.66	1994.19	3.37	3.19	4.67	6.73	4.40	5.08
23	1989.93	1992.89	1992.61	1994.18	2.96	2.73	4.25	6.15	4.63	4.67
24	1985.66	1990.91		1992.04	5.25		6.39	10.53		7.65
25	1984.31	1990.87	1991.09	1992.00	6.55	6.83	7.69	10.47	8.46	7.95
26	1985.31	1990.84		1991.95	5.53		6.65	8.32		6.61
27	1986.22	1990.82		1991.93	4.60		5.70	7.03		5.74
28	1987.50	1990.79		1991.94	3.29		4.44	5.82		4.92
29	1988.95	1990.74		1991.98	1.79		3.03	1.61		2.82
TailWater			1990.34							

Table A- 14. Numerical and Physical data from Full Choke condition at 40,000 cfs.

40 kcfs fully choked		WS Elevation (ft)			Depth (ft)			Velocity (fps)		
Test Location	Elevation	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*
1	1979.44	1997.65	1997.89	1998.90	18.2	18.45	19.5	5.1		4.6
2	1978.95	1997.72		1998.91	18.8		20.0	4.9		4.4
3	1979.07	1997.64		1998.90	18.6		19.8	4.9		4.4
4	1978.90	1997.62		1998.90	18.7		20.0	4.8		4.4
5	1989.38	1997.05		1998.49	7.7		9.1	8.4		6.9
6	1988.10	1996.98	1996.53	1998.57	8.9	8.43	10.5	8.8	8.78	7.2
7	1988.94	1996.83	1996.68	1998.42	7.9	7.66	9.5	8.5	9.07	7.0
8	1989.35	1996.81		1998.41	7.5		9.1	8.5		6.9
9	1989.86	1996.85	1996.58	1998.41	7.0	6.65	8.5	8.3	8.76	6.9
10	1991.02	1997.02	1996.69	1998.48	6.0	5.67	7.5	6.9	7.08	5.8
11	1991.49	1997.05	1996.65	1998.48	5.6	4.97	7.0	6.4	7.09	5.4
12	1989.03	1995.99		1997.52	7.0		8.5	9.1		7.2
13	1987.62	1995.89	1995.17	1997.48	8.3	7.60	9.9	9.6	9.96	7.8
14	1988.58	1995.80		1997.42	7.2		8.8	9.3		7.4
15	1989.50	1995.77		1997.38	6.3		7.9	8.9		7.0
16	1990.80	1995.69		1997.28	4.9		6.5	8.2		6.3
17	1991.21	1995.56		1997.16	4.4		5.9	7.9		6.1
18	1987.67	1993.85		1995.29	6.2		7.6	10.6		8.1
19	1986.33	1993.78	1993.79	1995.25	7.5	7.48	8.9	11.0	9.18	8.5
20	1987.32	1993.67	1993.74	1995.18	6.4	6.52	7.9	9.9	9.46	7.6
21	1988.24	1993.63	1993.66	1995.14	5.4	5.52	6.9	9.0	8.29	6.9
22	1989.51	1993.63	1993.77	1995.13	4.1	5.30	5.6	7.7	5.12	5.9
23	1989.93	1993.65	1993.65	1995.13	3.7	3.77	5.2	7.2	6.30	5.5
24	1985.66	1991.93		1993.07	6.3		7.4	10.8		8.3
25	1984.31	1991.96	1992.51	1993.06	7.7	8.25	8.8	10.3	8.35	8.3
26	1985.31	1991.98		1993.04	6.7		7.7	8.3		7.0
27	1986.22	1991.97		1993.03	5.8		6.8	7.2		6.3
28	1987.50	1991.97		1993.05	4.5		5.5	6.4		5.7
29	1988.95	1991.92		1993.07	3.0		4.1	2.0		3.7
TailWater			1992.01							

Table A- 15. Numerical and Physical data from Full Choke condition at 70,000 cfs.

70 kcfs fully choked		WS Elevation (ft)			Depth (ft)			Velocity (fps)		
Test Location	Elevation	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*	*N = 0.032*	*Ph. Model*	*N = 0.043*
1	1979.44	2000.42	2000.76	2002.10	21.0	21.32	22.7	7.3		6.8
2	1978.95	2000.49		2002.14	21.5		23.2	7.0		6.60
3	1979.07	2000.40		2002.14	21.3		23.1	7.0		6.58
4	1978.90	2000.38		2002.16	21.5		23.3	6.8		6.50
5	1989.38	1999.47		2001.50	10.1		12.1	10.9		9.42
6	1987.97	1999.23	1999.05	2001.38	11.3	10.95	13.4	11.3	10.38	9.82
7	1988.94	1999.18	1999.14	2001.34	10.2	10.12	12.4	11.1	10.80	9.57
8	1989.35	1999.14		2001.33	9.8		12.0	11.0		9.45
9	1989.86	1999.20	1998.97	2001.34	9.3	9.04	11.5	10.7	10.65	9.28
10	1991.02	1999.33	1999.14	2001.42	8.3	7.87	10.4	9.2	8.23	7.94
11	1991.49	1999.42	1999.13	2001.41	7.9	7.45	9.9	8.4	8.49	7.46
12	1989.03	1998.12		2000.32	9.1		11.3	11.9		9.77
13	1987.62	1997.99	1997.64	2000.25	10.4	10.07	12.6	12.2	10.87	10.18
14	1988.58	1997.87		2000.17	9.3		11.6	11.9		9.88
15	1989.50	1997.82		2000.12	8.3		10.6	11.6		9.52
16	1990.80	1997.65		1999.98	6.9		9.2	11.0		8.86
17	1991.21	1997.46		1999.83	6.3		8.6	10.8		8.69
18	1987.67	1995.88		1997.90	8.2		10.2	12.9		10.45
19	1986.33	1995.93	1996.36	1997.95	9.6	10.05	11.6	12.8	11.85	10.50
20	1987.32	1995.94	1996.56	1997.95	8.6	9.34	10.6	11.6	9.57	9.52
21	1988.24	1995.97	1996.49	1997.95	7.7	8.35	9.7	10.7	7.82	8.79
22	1989.51	1996.09	1996.57	1998.02	6.6	7.10	8.5	9.3	8.19	7.75
23	1989.93	1996.18	1996.66	1998.06	6.3	6.78	8.1	8.6	7.54	7.29
24	1985.66	1995.30		1996.41	9.6		10.8	10.9		9.48
25	1984.31	1995.35	1995.88	1996.46	11.0	11.62	12.2	9.8	7.84	8.95
26	1985.31	1995.40		1996.48	10.1		11.2	8.3		7.89
27	1986.22	1995.41		1996.49	9.2		10.3	7.8		7.47
28	1987.50	1995.44		1996.53	7.9		9.0	7.5		7.28
29	1988.95	1995.38		1996.52	6.4		7.6	3.6		5.76
TailWater			1995.40							

Comparison of Three Choke Conditions

Yellow highlighted rows were plotted and represent the upstream water surface elevation (1), centerline measurements at the crest (6), mid upper ramp slope (13), mid second ramp slope (19), and mid bottom slope (25).

Table A- 16. Data from three choked roughness condition at 7,000 cfs.

7k cfs		WS Elevation (ft)			Depth (ft)			Velocity (fps)		
Test Location	Elevation	*No Choke*	*Mid Choke*	*Full Choke*	*No Choke*	*Mid Choke*	*Full Choke*	*No Choke*	*Mid Choke*	*Full Choke*
1	1979.44	1992.49	1992.83	1992.82	13.06	13.39	13.38			
2	1978.95	1992.62			13.67					
3	1979.07	1992.74			13.67					
4	1978.90	1992.57			13.66					
5	1989.38									
6	1988.10	1991.42	1992.20	1992.27	3.32	4.10	4.17	6.78	4.97	5.09
7	1988.94									
8	1989.35									
9	1989.86									
10	1991.02									
11	1991.49									
12	1989.03									
13	1987.62	1991.18	1991.28	1991.45	3.61	3.71	3.88	4.02	4.46	5.50
14	1988.58									
15	1989.50									
16	1990.80									
17	1991.21									
18	1987.67									
19	1986.33	1989.02	1989.61	1989.79	2.71	3.30	3.48	4.36	5.09	4.48
20	1987.32									
21	1988.24									
22	1989.51									
23	1989.93									
24	1985.66									
25	1984.31	1986.94	1987.11	1987.23	2.68	2.85	2.97	4.07	4.39	5.72
26	1985.31									
27	1986.22									
28	1987.50									
29	1988.95									
TailWater		1985.79	1985.46	1985.28						

Table A- 17. Data from three choked roughness condition at 15,000 cfs.

15k cfs		WS Elevation (ft)			Depth (ft)			Velocity (fps)		
Test Location	Elevation	*No Choke*	*Mid Choke*	*Full Choke*	*No Choke*	*Mid Choke*	*Full Choke*	*No Choke*	*Mid Choke*	*Full Choke*
1	1979.44	1994.23	1994.54	1994.50	14.80	15.10	15.07			
2	1978.95	1994.34			15.39					
3	1979.07	1994.44			15.37					
4	1978.90	1994.19			15.29					
5	1989.38				3.83					
6	1987.97	1993.10	1993.68	1993.79	5.00	5.58	5.69	6.99	6.32	6.01
7	1988.94				4.00	4.77	5.00	7.85	6.60	6.36
8	1989.35				4.23					
9	1989.86				2.87	4.05	4.22	8.34	5.88	5.91
10	1991.02				2.22	2.47	2.75	6.18	6.11	5.40
11	1991.49									
12	1989.03									
13	1987.62	1992.58	1992.54	1992.78	4.97	4.97	5.21	6.51	6.98	7.78
14	1988.58									
15	1989.50									
16	1990.80									
17	1991.21									
18	1987.67									
19	1986.33	1990.91	1991.03	1991.22	4.59	4.72	4.91	5.49	6.67	7.34
20	1987.32				3.32	3.67	3.78	3.83	6.28	6.72
21	1988.24				2.52	2.65	2.75	3.54	4.06	5.55
22	1989.51				1.23	1.34	1.35	2.36	3.28	2.22
23	1989.93									
24	1985.66									
25	1984.31	1988.90	1988.94	1989.08	4.51	4.68	4.82	6.70	7.95	7.20
26	1985.31									
27	1986.22									
28	1987.50									
29	1988.95									
TailWater		1987.93	1987.63	1987.65						

Table A- 18. Data from three choked roughness condition at 30,000 cfs.

30k cfs		WS Elevation (ft)			Depth (ft)			Velocity (fps)		
Test Location	Elevation	*No Choke*	*Mid Choke*	*Full Choke*	*No Choke*	*Mid Choke*	*Full Choke*	*No Choke*	*Mid Choke*	*Full Choke*
1	1979.44	1996.50	1996.66	1996.67	17.06	17.22	17.23			
2	1978.95	1996.62			17.67					
3	1979.07	1996.59			17.52					
4	1978.90	1996.54			17.64					
5	1989.38				6.23					
6	1988.10	1995.00	1995.42	1995.52	6.92	7.32	7.42	8.30	7.73	8.00
7	1988.94		1995.47	1995.71	5.86	6.45	6.69	8.58	7.85	8.04
8	1989.35				6.08					
9	1989.86		n	1995.78	4.96	n	5.85	8.06	n	7.38
10	1991.02		1995.58	1995.70	3.87	4.31	4.43	7.48	6.76	6.82
11	1991.49		1995.35	1995.76	3.49	3.67	4.08	7.35	6.93	6.41
12	1989.03									
13	1987.62	1994.38	1994.43	1994.44	6.82	6.86	6.87	8.16	8.07	9.04
14	1988.58									
15	1989.50									
16	1990.80									
17	1991.21									
18	1987.67									
19	1986.33	1993.01	1992.89	1992.86	6.71	6.58	6.55	7.87	8.71	8.68
20	1987.32		1992.76	1992.67	5.38	5.54	5.45	5.86	6.81	8.74
21	1988.24		n	1992.65	4.63	n	4.51	5.74	n	7.90
22	1989.51		1992.80	1992.66	3.40	3.33	3.19	4.14	4.61	4.40
23	1989.93		1992.82	1992.61	2.57	2.94	2.73	2.69	3.42	4.63
24	1985.66									
25	1984.31	1991.50	1991.15	1991.09	7.26	6.89	6.83	7.38	7.57	8.46
26	1985.31									
27	1986.22									
28	1987.50									
29	1988.95									
TailWater		1990.39	1990.39	1990.34						

Table A- 19. Data from three choked roughness condition at 40,000 cfs.

40k cfs		**WS Elevation (ft)**			**Depth (ft)**			**Velocity (fps)**		
Test Location	Elevation	*No Choke*	*Mid Choke*	*Full Choke*	*No Choke*	*Mid Choke*	*Full Choke*	*No Choke*	*Mid Choke*	*Full Choke*
1	1979.44	1997.70	1997.93	1997.89	18.26	18.49	18.45			
2	1978.95	1997.82			18.87					
3	1979.07	1997.82			18.75					
4	1978.90	1997.62			18.71					
5	1989.38				7.21					
6	1987.97	1996.20	1996.51	1996.53	8.10	8.41	8.43	8.98	8.16	8.78
7	1988.94		1996.48	1996.68	6.97	7.46	7.66	9.21	8.65	9.07
8	1989.35				7.92					
9	1989.86		1996.47	1996.58	5.97	6.54	6.65	9.06	8.34	8.76
10	1991.02		1996.61	1996.69	4.99	5.34	5.67	7.64	7.30	7.08
11	1991.49		1996.39	1996.65	4.53	4.71	4.97	7.70	7.42	7.09
12	1989.03									
13	1987.62	1995.44	1995.11	1995.17	7.87	7.54	7.60	8.90	9.26	9.96
14	1988.58									
15	1989.50									
16	1990.80									
17	1991.21									
18	1987.67									
19	1986.33	1994.21	1993.90	1993.79	7.90	7.59	7.48	8.32	9.54	9.18
20	1987.32		1993.88	1993.74	6.69	6.66	6.52	5.75	7.77	9.46
21	1988.24		1993.88	1993.66	5.95	5.74	5.52	5.99	6.88	8.29
22	1989.51		1993.96	1993.77	4.74	4.49	5.30	5.06	5.49	5.12
23	1989.93		1993.99	1993.65	3.90	4.11	3.77	3.98	4.81	6.30
24	1985.66									
25	1984.31	1992.86	1992.61	1992.51	8.60	8.35	8.25	6.84	7.39	8.35
26	1985.31									
27	1986.22									
28	1987.50									
29	1988.95									
TailWater		1992.23	1992.05	1992.01						

Table A- 20. Data from three choked roughness condition at 70,000 cfs.

70k cfs		**WS Elevation (ft)**			**Depth (ft)**			**Velocity (fps)**		
Test Location	Elevation	*No Choke*	*Mid Choke*	*Full Choke*	*No Choke*	*Mid Choke*	*Full Choke*	*No Choke*	*Mid Choke*	*Full Choke*
1	1979.44	2000.78	2000.86	2000.76	21.34	21.42	21.32			
2	1978.95	2000.64			21.69					
3	1979.07	2000.67			21.60					
4	1978.90	2000.59			21.69					
5	1989.38				9.21					
6	1987.97	1998.93	1999.08	1999.05	10.83	10.98	10.95	10.39	9.51	10.38
7	1988.94		1999.04	1999.14	9.71	10.02	10.12	10.50	9.95	10.80
8	1989.35				10.36					
9	1989.86		1998.95	1998.97	8.68	9.02	9.04	10.68	10.10	10.65
10	1991.02		1999.23	1999.14	7.69	7.96	7.87	8.47	7.97	8.23
11	1991.49		1999.01	1999.13	7.22	7.33	7.45	8.55	8.37	8.49
12	1989.03									
13	1987.62	1997.92	1997.71	1997.64	10.35	10.14	10.07	8.84	10.74	10.87
14	1988.58									
15	1989.50									
16	1990.80									
17	1991.21									
18	1987.67									
19	1986.33	1997.04	1996.68	1996.36	10.73	10.37	10.05	8.59	10.18	11.85
20	1987.32		1996.63	1996.56	9.62	9.41	9.34	8.10	8.85	9.57
21	1988.24		1996.68	1996.49	8.89	8.54	8.35	7.53	7.65	7.82
22	1989.51		1996.82	1996.57	7.72	7.35	7.10	6.21	6.98	8.19
23	1989.93		1996.88	1996.66	6.90	7.00	6.78	5.68	6.55	7.54
24	1985.66									
25	1984.31	1996.10	1995.85	1995.88	11.84	11.59	11.62	7.55	8.37	7.84
26	1985.31									
27	1986.22									
28	1987.50									
29	1988.95									
TailWater		1995.69	1995.42	1995.40						

Appendix B

Boulder Field Crest Velocity Comparison for Grids 1 through 7 – All data at 30,000 cfs

Initial boulder testing included data at various sections on the ramp. Grids 4 through 7 focused on velocities only on the weir crest.

Table B- 1 Data from baseline condition compared to Grids 1 and 2 at 30,000 cfs.

Section	Test Location	Depth (ft)			Velocity (fps)		
		Base Line	*G1-36 Boulders*	*G2-72 Boulders*	*Base Line*	*G1-36 Boulders*	*G2-72 Boulders*
A	C	7.42	7.42	7.46	8.00	8.34	8.21
	R1	6.69	6.66	6.77	8.04	8.25	8.34
	R2	5.85	5.83	5.93	7.38	7.25	7.35
	R3	4.58	4.64	4.78	8.66	8.41	8.49
	R4	4.43	4.39	4.52	6.82	6.41	6.38
	R5	4.08	3.92	4.02	6.41	6.67	6.72
B	R1				7.86	8.03	7.17
	R2				5.85	6.63	7.76
	R3				5.06	7.47	6.51
	R4					6.58	5.27
	R5					5.52	5.77
C	C	6.87	6.93	6.96	9.04	8.47	9.31
	R1	5.90	5.89	6.07	8.80	8.79	9.00
	R2	5.07	4.99	5.12	7.64	7.40	7.53
	R3	4.72	4.78	4.67	6.26	6.64	6.28
	R4	3.58	3.56	3.76	7.13	5.56	5.38
	R5	3.12	3.20	3.46	5.69	5.66	6.32
D	R1				9.10	6.60	7.27
	R2				6.98	7.34	7.12
	R3				3.25	6.24	5.73
	R4						
	R5						
E	C	6.55	6.45		8.68	5.30	
	R1	5.45	5.45		8.74	8.11	
	R2	4.51	4.44		7.90	7.33	
	R3	3.85	4.61		4.57	5.23	
	R4	3.19	3.11		4.40	4.93	
	R5	2.73	2.62		4.63	4.37	
F	R1				8.06	7.83	
	R2				8.60	9.09	
	R3						
	R4						
	R5						
G	C	6.83	6.90		8.46	3.83	
	R1	5.97	6.00		2.44	1.87	
	R2	5.14	5.12		1.70	3.69	
	R3	3.71	3.71		4.95	4.44	
	R4					3.46	
H	R1				7.25	5.87	
	R2				5.07	5.70	
	R3				4.53	5.08	
Head Water W.S. El.		1996.65	1996.68	1996.73			
Tail Water W.S. El.		1990.36	1990.36	1990.38			

Table B- 2. Data from baseline condition compared to Grid 4 at 30,000 cfs.

Section	Test Location	Depth (ft)				Velocity (fps)			
		Base Line	*Grid 4-Full*	*Grid 4 - 2/3*	*Grid 4 - 1/3*	*Base Line*	*Grid 4-Full*	*Grid 4 - 2/3*	*Grid 4 - 1/3*
A	C	7.42	7.61	7.50	7.53	8.00	8.63	8.61	8.49
	R1	6.69	6.58	6.73	6.75	8.04	8.66	8.61	8.60
	R2	5.85	5.67	5.87	5.88	7.38	7.64	7.68	7.58
	R3	4.58	4.51	4.85	4.80	8.66	8.33	8.58	8.60
	R3.5		4.58	4.72	4.65		7.26	7.51	7.80
	R4	4.43	4.65	4.58	4.50	6.82	6.01	6.24	6.55
	R4.5		4.48	4.41	4.34		6.23	6.31	6.53
	R5	4.08	4.22	4.14	4.05	6.41	6.07	5.94	6.10
	R5.5		3.96	3.86	3.77		5.79	6.18	6.36
	R6		3.94	3.78	3.55		5.61	5.85	6.79
Head Water W.S. El.		1996.65	1996.77	1996.74	1996.70				
Tail Water W.S. El.		1990.36	1990.38	1990.38	1990.40				

Table B- 3. Data from baseline condition compared to Grids 5, 6, and 7 at 30,000 cfs.

Section	Test Location	Depth (ft)				Velocity (fps)			
		Base Line	*Grid 5: 5-3 D*	*Grid 6: Offset*	*Grid 7*	*Base Line*	*Grid 5: 5-3 D*	*Grid 6: Offset*	*Grid 7*
A	C	7.42	7.53	7.55	7.60	8.00	8.71	8.54	8.49
	R1	6.69	6.74	6.76	6.78	8.04	8.51	8.49	8.46
	R2	5.85	5.86	5.90	5.91	7.38	7.64	7.57	7.52
	R3	4.58	4.80	4.82	4.85	8.66	8.62	8.66	8.65
	R3.5		4.68	4.69	4.73		7.72	7.77	7.78
	R4	4.43	4.56	4.57	4.61	6.82	6.19	6.25	6.02
	R4.5		4.42	4.42	4.46		6.25	6.46	6.07
	R5	4.08	4.12	4.05	4.17	6.41	6.09	5.77	6.23
	R5.5		3.80	3.78	3.88		6.21	5.58	6.16
	R6		3.65	3.69	3.61		6.63	5.30	6.48
Head Water W.S. El.		1996.65	1996.71	1996.70	1996.74				
Tail Water W.S. El.		1990.36	1990.38	1990.35	1990.38				

Planview Velocity Data for Ramp with Boulder Field – Green hatch indicates areas where velocity was less than 6 ft/s

Red lines indicate shortened ramp geometry.

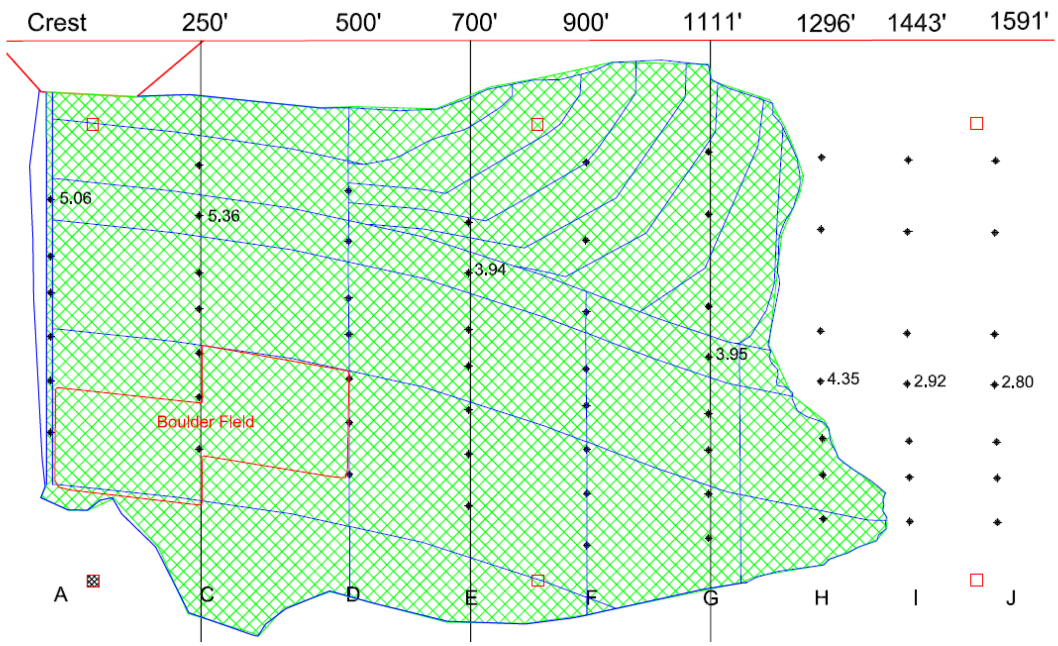

Figure B- 1. Planview velocity data with boulder field at 7,000 cfs.

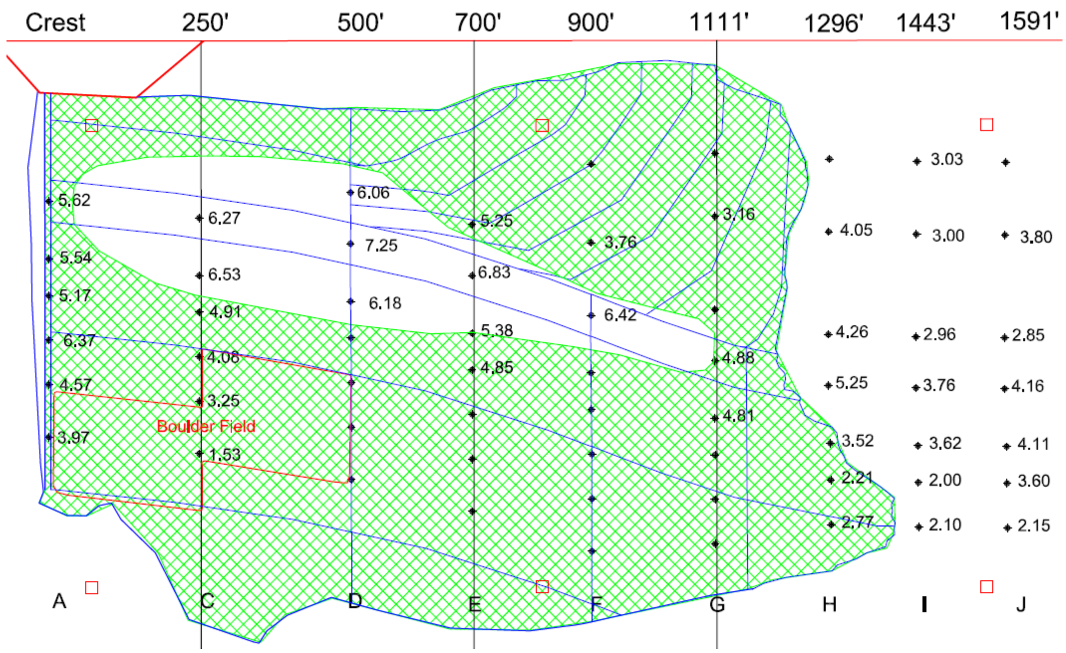

Figure B- 2. Planview velocity data with boulder field at 15,000 cfs.

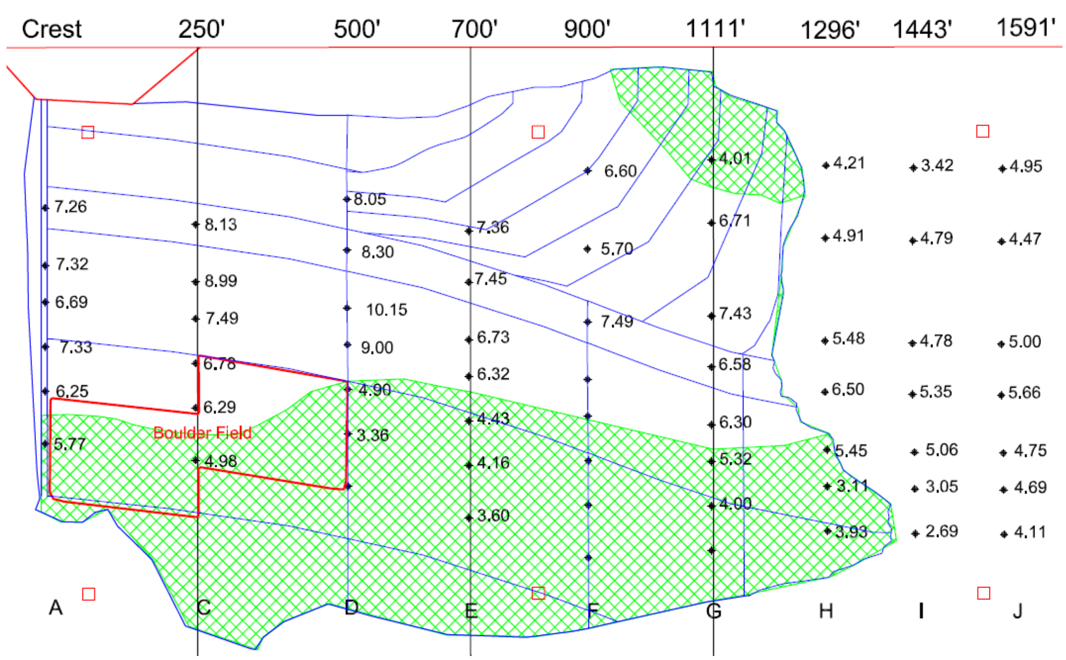

Figure B- 3. Planview velocity data with boulder field at 30,000 cfs.

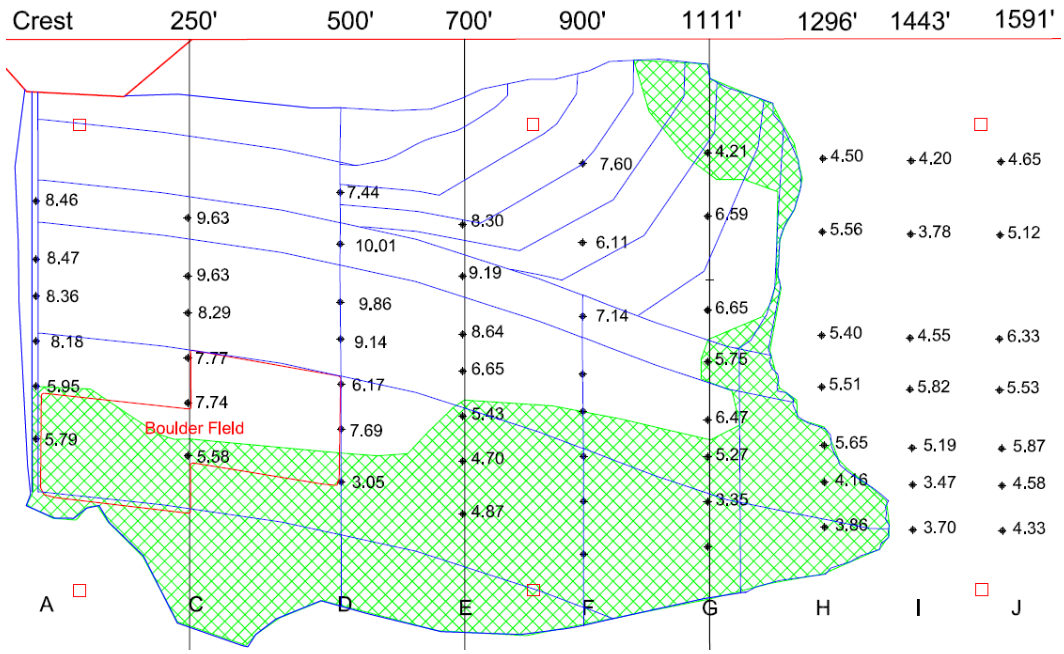

Figure B- 4. Planview velocity data with boulder field at 40,000 cfs.

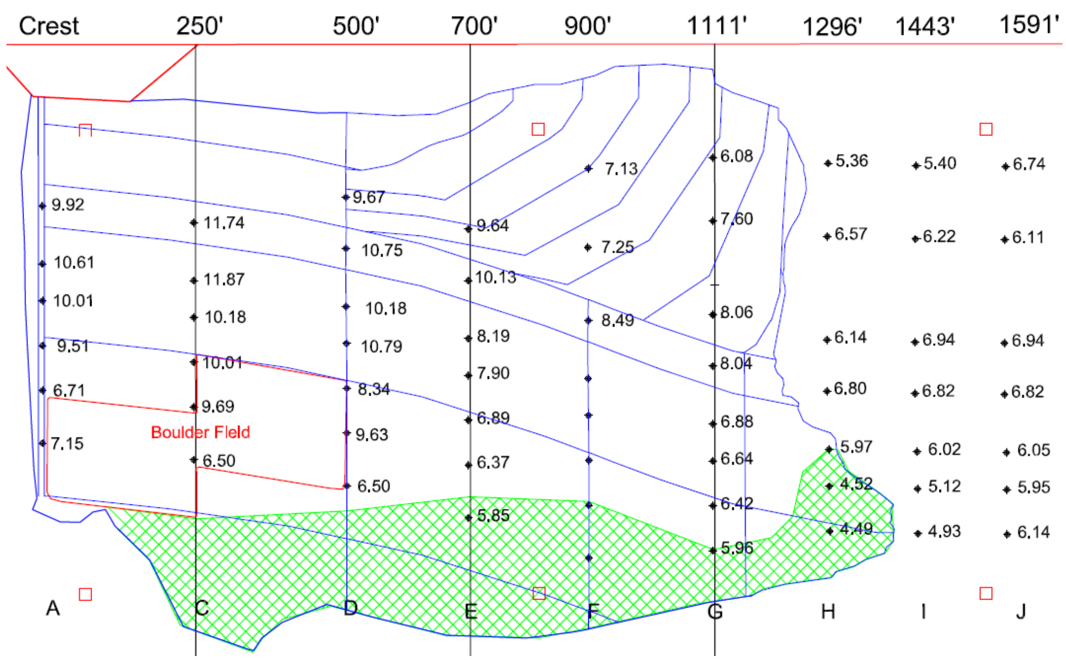

Figure B- 5. Planview velocity data with boulder field at 70,000 cfs.

Appendix C

Comparison of Physical Model Depth and Velocity Data from C1 and C2 Ramp Geometry

Table C- 1. Original and shortened ramp data at 7,000 cfs.

	Q = 7,000 cfs		Original	Modified	Original	Modified
	Distance D/S Crest	Test Location	Velocity	Velocity	Depth	Depth
	ft		*fps*	*fps*	*ft*	*ft*
A	0	C		5.06		3.87
		R1				
		R2				
		R3				
		R4				
		R5				
C	250	C		5.36		3.60
		R1				
		R2				
		R3				
		R4				
		R5				
D	500	L				
		C				
		R1				
		R2				
		R3				
		R4				
		R5				
E	700	L				
		C	4.48	3.94	3.48	3.04
		R1				
		R2				
		R3				
		R4				
		R5				
F	900	L2				
		L1				
		C				
		R1				
		R2				
		R3				
		R4				
		R5				
G	1111	L3				
		L2				
		L1				
		C	5.72	3.95	2.97	2.68
		R1				
		R2				
		R3				
H	1296	L3				
		L2				
		L1				
		C	3.31	4.35	2.16	2.77
		R1				
		R2				
		R3				
I	1443	L3				
		L2				
		L1				
		C	3.86	2.92	3.28	3.37
		R1				
		R2				
		R3				
J	1591	L3				
		L2				
		L1				
		C	4.02	2.80	4.28	4.17
		R1				
		R2				
		R3				
		HW Elev.	1992.82	1992.63		
		TW Elev.	1985.28	1985.37		

Table C- 2. Original and shortened ramp data at 15,000 cfs.

	Q = 15,000 cfs		Original	Modified	Original	Modified
	Distance D/S Crest	Test Location	Velocity	Velocity	Depth	Depth
	ft		fps	fps	ft	ft
A	0	C		5.62		5.53
		R1		5.54		4.79
		R2		5.17		4.03
		R3		6.37		2.92
		R4		4.57		2.53
		R5		3.97		2.14
C	250	C		6.27		5.08
		R1		6.53		4.09
		R2		4.91		3.21
		R3		4.08		2.63
		R4		3.25		1.76
		R5		1.53		1.16
D	500	L		6.06		
		C		7.25		
		R1		6.18		
		R2				
		R3				
		R4				
		R5				
E	700	L		5.25		3.16
		C	7.34	6.83	4.91	4.40
		R1	6.72	5.38	3.78	3.46
		R2	5.55	4.85	2.75	2.39
		R3				
		R4	2.22		1.35	
		R5				
F	900	L2		3.76		
		L1		6.42		
		C				
		R1				
		R2				
		R3				
		R4				
		R5				
G	1111	L3				
		L2		3.16		3.37
		L1			2.90	3.16
		C	7.20	4.88	4.82	4.41
		R1		4.81		3.39
		R2				
		R3				
H	1296	L3				4.59
		L2		4.05		4.79
		L1	6.63	4.26	3.27	4.59
		C	3.97	5.25	4.52	4.99
		R1	6.06	3.52	3.63	4.69
		R2	5.93	2.21	2.70	4.19
		R3		2.77		3.59
I	1443	L3		3.03		4.59
		L2		3.00		4.89
		L1	4.17	2.96	4.25	4.59
		C	4.80	3.76	5.64	5.59
		R1	5.30	3.62	4.98	5.59
		R2	3.63	2.00	3.73	5.59
		R3	2.80	2.10	3.48	4.99
J	1591	L3				
		L2		3.80		4.99
		L1	4.31	2.85	4.84	4.59
		C	4.56	4.16	6.64	6.39
		R1	5.30	4.11	6.35	6.59
		R2	3.86	3.60	4.76	5.39
		R3	3.60	2.15	4.48	4.59
		HW Elev.	1994.53	1994.45		
		TW Elev.	1987.64	1987.59		

Table C- 3. Original and shortened ramp data at 30,000 cfs.

	Q = 30,000 cfs		Original	Modified	Original	Modified
	Distance D/S Crest	Test Location	Velocity	Velocity	Depth	Depth
	ft		fps	fps	ft	ft
A	0	C	8.54	7.26	7.55	7.25
		R1	8.49	7.32	6.76	6.50
		R2	7.57	6.69	5.90	5.56
		R3	8.66	7.82	4.82	4.54
		R3.5	7.77	8.03	4.69	4.01
		R4	6.25	6.54	4.57	4.33
		R4.5	6.46	5.99	4.42	4.20
		R5	5.77	6.12	4.05	3.88
		R5.5	5.58	5.74	3.78	3.63
		R6	5.30	5.53	3.69	3.50
C	250	C		8.13		6.86
		R1		8.99		5.90
		R2		7.49		5.03
		R3		6.78		4.57
		R4		6.29		3.64
		R5		4.98		2.94
D	500	L		8.05		
		C		8.30		
		R1		10.15		
		R2		9.00		
		R3		4.90		
		R4		3.36		
		R5				
E	700	L		7.36		4.89
		C	8.68	7.45	6.55	6.24
		R1	8.74	6.73	5.45	4.99
		R2	7.90	6.32	4.51	4.22
		R3		4.43		3.68
		R4	4.40	4.16	3.19	3.05
		R5	4.63	3.60	2.73	2.48
F	900	L2		6.60		
		L1		5.70		
		C		7.49		
		R1				
		R2				
		R3				
		R4				
		R5				
G	1111	L3	2.85	4.01	3.10	4.97
		L2	5.04	6.71	3.50	5.24
		L1	4.62	7.43	5.02	5.59
		C	8.46	6.58	6.83	6.87
		R1		6.30	5.97	5.92
		R2		5.32	5.14	4.95
		R3	4.95	4.00	3.71	3.00
		R4				
H	1296	L3	4.81	4.21	9.94	13.64
		L2	3.54	4.91	10.26	13.84
		L1	7.40	5.48	12.33	13.64
		C	5.89	6.50	13.58	14.04
		R1	6.88	5.45	12.69	13.74
		R2	5.52	3.11	11.76	13.24
		R3	5.10	3.93	10.84	12.64
I	1443	L3	3.92	3.42	11.19	13.64
		L2	2.75	4.79	11.53	13.94
		L1	4.71	4.78	13.31	13.64
		C	5.40	5.35	14.70	14.64
		R1	6.35	5.06	14.04	14.64
		R2	5.25	3.05	12.79	14.64
		R3	3.78	2.69	12.54	14.04
J	1591	L3	3.50	4.95	12.48	13.64
		L2	2.25	4.47	13.02	14.04
		L1	5.25	5.00	13.90	13.64
		C	6.19	5.66	15.70	15.44
		R1	6.07	4.75	15.41	15.64
		R2	5.28	4.69	13.82	14.44
		R3	5.12	4.11	13.54	13.64
		HW Elev.	1996.70	1996.64		
		TW Elev.	1990.36	1990.39		

Table C- 4. Original and shortened ramp data at 40,000 cfs.

	Q = 40,000 cfs		Original	Modified	Original	Modified
	Distance D/S Crest	Test Location	Velocity	Velocity	Depth	Depth
	ft		fps	fps	ft	ft
A	0	C		8.46		8.26
		R1		8.47		7.39
		R2		8.36		6.36
		R3		8.18		5.49
		R4		5.95		5.40
		R5		5.79		5.00
C	250	C		9.63		7.90
		R1		9.63		6.81
		R2		8.29		5.89
		R3		7.77		5.40
		R4		7.74		4.63
		R5		5.58		3.82
D	500	L		7.44		
		C		10.01		
		R1		9.86		
		R2		9.14		
		R3		6.17		
		R4		7.69		
		R5		3.05		
E	700	L		8.30		5.78
		C	9.18	9.19	7.48	7.06
		R1	9.46	8.64	6.52	6.34
		R2	8.29	6.65	5.52	5.27
		R3		5.43		4.80
		R4	5.12	4.70	5.30	4.19
		R5	6.30	4.87	3.77	3.61
F	900	L2		7.60		
		L1		6.11		
		C		7.14		
		R1				
		R2				
		R3				
		R4				
		R5				
G	1111	L3	4.40	4.21	4.40	6.51
		L2	5.32	6.59	5.32	6.73
		L1	4.73	6.65	4.73	7.09
		C	8.35	5.75	8.25	8.40
		R1	4.65	6.47	7.46	7.41
		R2	4.88	5.27	6.63	6.43
		R3	5.77	3.35	5.20	4.47
		R4	4.31			
H	1296	L3	4.25	4.50	11.13	14.86
		L2	5.89	5.56	11.45	15.06
		L1	7.45	5.40	13.52	14.86
		C	6.97	5.51	14.77	15.26
		R1	7.08	5.65	13.88	14.96
		R2	6.01	4.16	12.95	14.46
		R3	5.30	3.86	12.03	13.86
I	1443	L3	4.04	4.20	12.38	14.86
		L2	4.00	3.78	12.72	15.16
		L1	6.45	4.55	14.50	14.86
		C	5.70	5.82	15.89	15.86
		R1	5.21	5.19	15.23	15.86
		R2	4.90	3.47	13.98	15.86
		R3	4.35	3.70	13.73	15.26
J	1591	L3	4.40	4.65	13.67	14.86
		L2	5.00	5.12	14.21	15.26
		L1	6.44	6.33	15.09	14.86
		C	6.52	5.53	16.89	16.66
		R1	5.12	5.87	16.60	16.86
		R2	5.91	4.58	15.01	15.66
		R3	5.60	4.33	14.73	14.86
		HW Elev.	1997.89	1997.86		
		TW Elev.	1992.01	1992.02		

Table C- 5. Original and shortened ramp data at 70,000 cfs.

	Q = 70,000 cfs		Original	Modified	Original	Modified
	Distance D/S Crest	Test Location	Velocity	Velocity	Depth	Depth
	ft		fps	fps	ft	ft
A	0	C		9.92		10.85
		R1		10.61		9.95
		R2		10.01		8.94
		R3		9.51		8.08
		R4		6.71		8.05
		R5		7.15		7.57
C	250	C		11.74		9.94
		R1		11.87		9.11
		R2		10.18		8.51
		R3		10.01		7.82
		R4		9.69		7.12
		R5		8.00		6.52
D	500	L		9.67		
		C		10.75		
		R1		10.18		
		R2		10.79		
		R3		8.34		
		R4		9.63		
		R5		6.50		
E	700	L		9.64		8.54
		C	11.85	10.13	10.05	9.66
		R1	9.57	8.19	9.34	9.31
		R2	7.82	7.90	8.35	8.21
		R3		6.89		7.78
		R4	8.19	6.37	7.10	7.24
		R5	7.54	5.85	6.78	6.68
F	900	L2		7.13		
		L1		7.25		
		C		8.49		
		R1				
		R2				
		R3				
		R4				
		R5				
G	1111	L3	5.06	6.08	7.63	9.88
		L2	6.61	7.60	7.97	10.05
		L1	6.21	8.06	9.80	10.42
		C	7.84	8.04	11.62	11.75
		R1	7.20	6.88	10.85	10.77
		R2	6.92	6.64	10.00	9.79
		R3	6.28	6.42	8.59	7.86
		R4	5.71	5.96		
H	1296	L3	5.86	5.36	14.02	17.80
		L2	7.08	6.57	14.34	18.00
		L1	7.95	6.14	16.41	17.80
		C	6.33	6.80	17.66	18.20
		R1	6.76	5.97	16.77	17.90
		R2	6.67	4.52	15.84	17.40
		R3	6.25	4.49	14.92	16.80
I	1443	L3	5.85	5.40	15.27	17.80
		L2	6.20	6.22	15.61	18.10
		L1	7.01	6.94	17.39	17.80
		C	6.32	6.82	18.78	18.80
		R1	6.51	6.02	18.12	18.80
		R2	5.72	5.12	16.87	18.80
		R3	5.30	4.93	16.62	18.20
J	1591	L3	6.50	6.74	16.56	17.80
		L2	6.55	6.11	17.10	18.20
		L1	7.20	6.94	17.98	17.80
		C	7.91	6.82	19.78	19.60
		R1	6.65	6.05	19.49	19.80
		R2	6.50	5.95	17.90	18.60
		R3	6.71	6.14	17.62	17.80
		HW Elev.	2000.78	2000.80		
		TW Elev.	1995.44	1995.44		

Depth and Velocity Data from Shortened Ramp Geometry with and without Grid 6 Boulder Field

Data taken only for the first 900 ft downstream of the crest.

Table C- 6. Shortened ramp data with and without a boulder field at 15,000 cfs.

	Q = 15,000 cfs		No Boulder Field	Boulder Field	No Boulder Field	Boulder Field
	Distance D/S Crest	Test Location	Velocity	Velocity	Depth	Depth
	ft		fps	fps	ft	ft
A	0	C	6.28	5.62	5.43	5.53
		R1	6.30	5.54	4.70	4.79
		R2	6.14	5.17	3.92	4.03
		R3	7.14	6.37	2.74	2.92
		R4	5.79	4.57	2.37	2.53
		R5	4.92	3.97	2.03	2.14
C	250	C	6.67	6.27	4.93	5.08
		R1	5.92	6.53	3.90	4.09
		R2	4.91	4.91	3.05	3.21
		R3	4.28	4.08	2.43	2.63
		R4	5.90	3.25	1.51	1.76
		R5	1.66	1.53	1.00	1.16
D	500	L	5.35	6.06		
		C	5.15	7.25		
		R1		6.18		
		R2				
		R3				
		R4				
		R5				
E	700	L	5.75	5.25	2.98	3.16
		C	5.98	6.83	4.11	4.40
		R1	6.17	5.38	3.29	3.46
		R2	4.50	4.85	2.20	2.39
		R3	2.39		1.66	
		R4	2.96		0.97	
		R5				
F	900	L2		3.76		
		L1		6.42		
		C	5.70			
		R1				
		R2				
		R3				
		R4				
		R5				

Table C- 7. Shortened ramp data with and without a boulder field at 30,000 cfs.

	Q = 30,000 cfs		No Boulder Field	Boulder Field	No Boulder Field	Boulder Field
	Distance D/S Crest	Test Location	Velocity	Velocity	Depth	Depth
	ft		*fps*	*fps*	*ft*	*ft*
A	0	C	7.84	8.54	7.20	7.25
		R1	7.68	8.49	6.41	6.50
		R2	6.71	7.57	5.67	5.56
		R3	8.10	8.66	4.34	4.54
		R3.5	8.40	7.77	3.79	4.01
		R4	6.99	6.25	4.13	4.33
		R4.5	6.16	6.46	4.04	4.20
		R5	6.98	5.77	3.57	3.88
		R5.5	7.12	5.58	3.20	3.63
		R6	6.77	5.30	3.00	3.50
C	250	C	9.05	8.13	6.78	6.86
		R1	7.93	8.99	5.70	5.90
		R2	7.37	7.49	4.83	5.03
		R3	6.42	6.78	4.34	4.57
		R4	6.11	6.29	3.50	3.64
		R5	4.90	4.98	2.93	2.94
D	500	L	6.60	8.05		
		C	7.40	8.30		
		R1	7.19	10.15		
		R2	7.33	9.00		
		R3	6.62	4.90		
		R4		3.36		
		R5				
E	700	L	7.41	7.36	4.74	4.89
		C	7.21	7.45	6.18	6.24
		R1	7.34	6.73	5.30	4.99
		R2	6.34	6.32	4.23	4.22
		R3	5.22	4.43	3.64	3.68
		R4	4.86	4.16	3.10	3.05
		R5	3.73	3.60	2.46	2.48
F	900	L2		6.60		
		L1	4.22	5.70		
		C	7.97	7.49		
		R1	7.18			
		R2	6.18			
		R3				
		R4				
		R5				

Table C- 8. Shortened ramp data with and without a boulder field at 40,000 cfs.

	Q = 40,000 cfs		No Boulder Field	Boulder Field	No Boulder Field	Boulder Field
	Distance D/S Crest	Test Location	Velocity	Velocity	Depth	Depth
	ft		fps	fps	ft	ft
A	0	C	8.68	8.46	8.19	8.26
		R1	8.85	8.47	7.33	7.39
		R2	9.00	8.36	7.17	6.36
		R3	8.49	8.18	5.33	5.49
		R4	6.78	5.95	5.13	5.40
		R5	6.67	5.79	4.69	5.00
C	250	C	10.57	9.63	7.75	7.90
		R1	8.64	9.63	6.37	6.81
		R2	8.67	8.29	6.78	5.89
		R3	7.63	7.77	5.24	5.40
		R4	6.93	7.74	4.44	4.63
		R5	5.54	5.58	4.03	3.82
D	500	L	8.30	7.44		
		C	8.62	10.01		
		R1	8.18	9.86		
		R2	9.30	9.14		
		R3	6.96	6.17		
		R4	6.11	7.69		
		R5	6.67	3.05		
E	700	L	9.27	8.30	5.64	5.78
		C	9.26	9.19	6.95	7.06
		R1	8.47	8.64	7.06	6.34
		R2	7.03	6.65	5.27	5.27
		R3	6.14	5.43	4.79	4.80
		R4	5.80	4.70	4.24	4.19
		R5	5.21	4.87	3.67	3.61
F	900	L2	7.65	7.60		
		L1	7.01	6.11		
		C	7.78	7.14		
		R1	7.80			
		R2				
		R3				
		R4				
		R5				

Table C- 9. Shortened ramp data with and without a boulder field at 70,000 cfs.

	Q = 70,000 cfs		No Boulder Field	Boulder Field	No Boulder Field	Boulder Field
	Distance D/S Crest	Test Location	Velocity	Velocity	Depth	Depth
	ft		*fps*	*fps*	*ft*	*ft*
A	0	C	10.06	9.92	10.79	10.85
		R1	10.65	10.61	9.84	9.95
		R2	10.58	10.01	8.81	8.94
		R3	9.94	9.51	7.90	8.08
		R4	7.69	6.71	7.79	8.05
		R5	7.74	7.15	7.32	7.57
C	250	C	10.73	11.74	9.71	9.94
		R1	10.60	11.87	8.80	9.11
		R2	10.08	10.18	8.25	8.51
		R3	9.05	10.01	7.53	7.82
		R4	8.12	9.69	6.70	7.12
		R5	8.62	8.00	6.31	6.52
D	500	L	10.56	9.67		
		C	9.47	10.75		
		R1	10.74	10.18		
		R2	10.22	10.79		
		R3	9.47	8.34		
		R4	9.76	9.63		
		R5	8.83	6.50		
E	700	L	10.42	9.64	8.49	8.54
		C	11.06	10.13	9.64	9.66
		R1	7.93	8.19	9.10	9.31
		R2	8.44	7.90	8.25	8.21
		R3	7.64	6.89	7.72	7.78
		R4	7.25	6.37	7.23	7.24
		R5	6.96	5.85	6.76	6.68
F	900	L2	7.27	7.13		
		L1	7.72	7.25		
		C	8.31	8.49		
		R1	8.28			
		R2	7.90			
		R3				
		R4				
		R5				

Planview Velocity Data from Shortened Ramp Geometry (C2) – Green hatch indicates areas where velocity was less than 6 ft/s

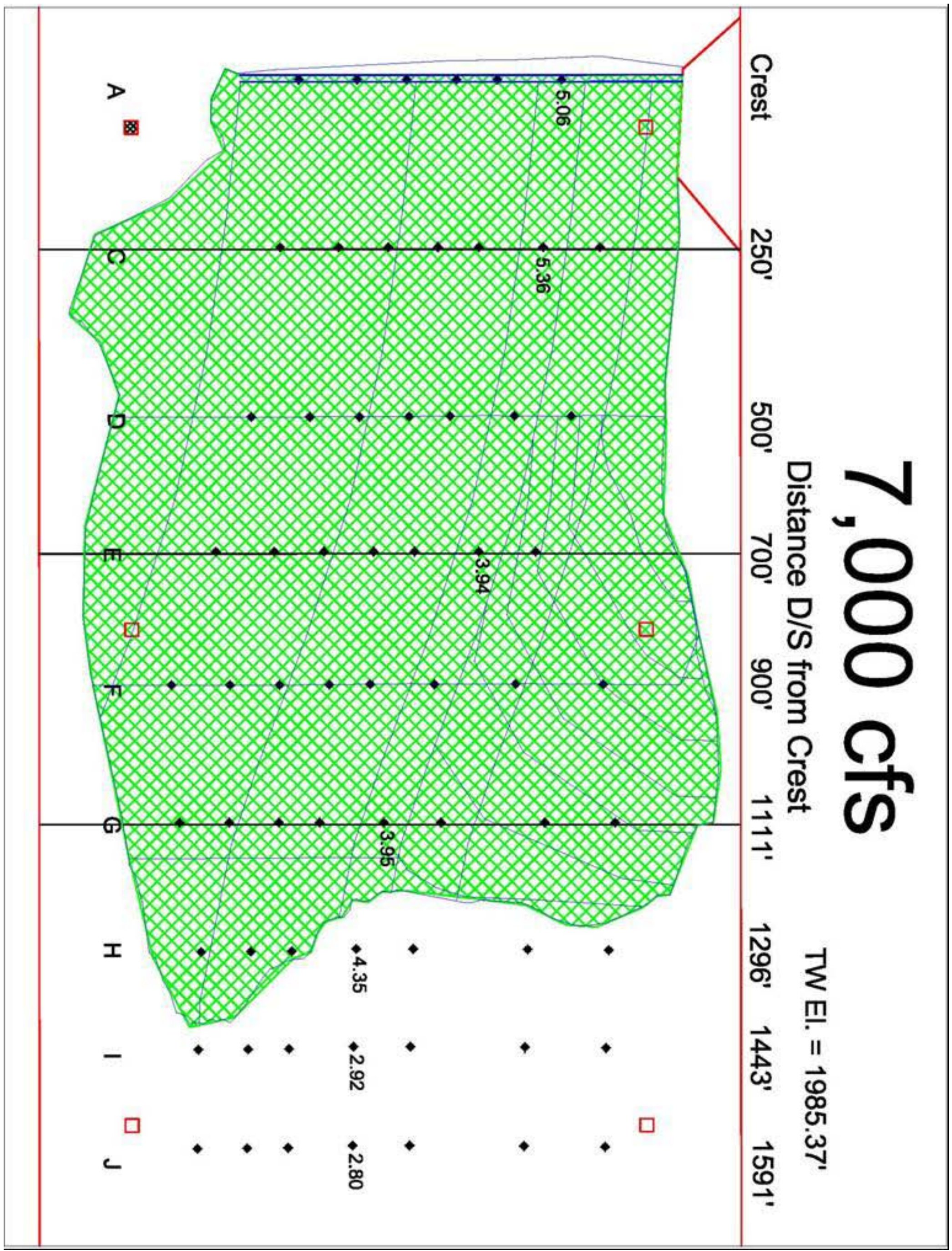

Figure C- 1. Planview velocity data of shortened ramp geometry without a boulder field at 7,000 cfs.

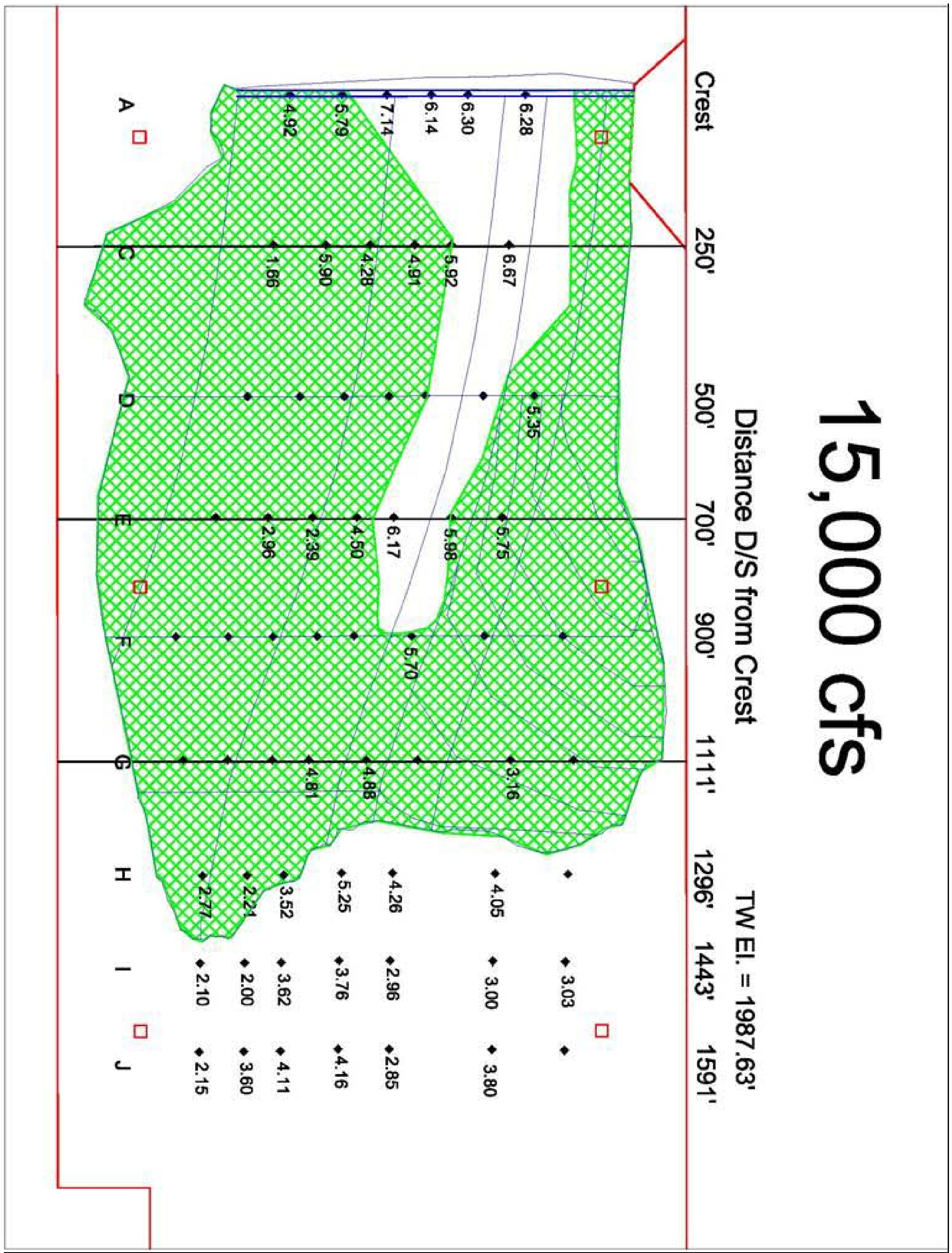

Figure C- 2. Planview velocity data of shortened ramp geometry without a boulder field at 15,000 cfs.

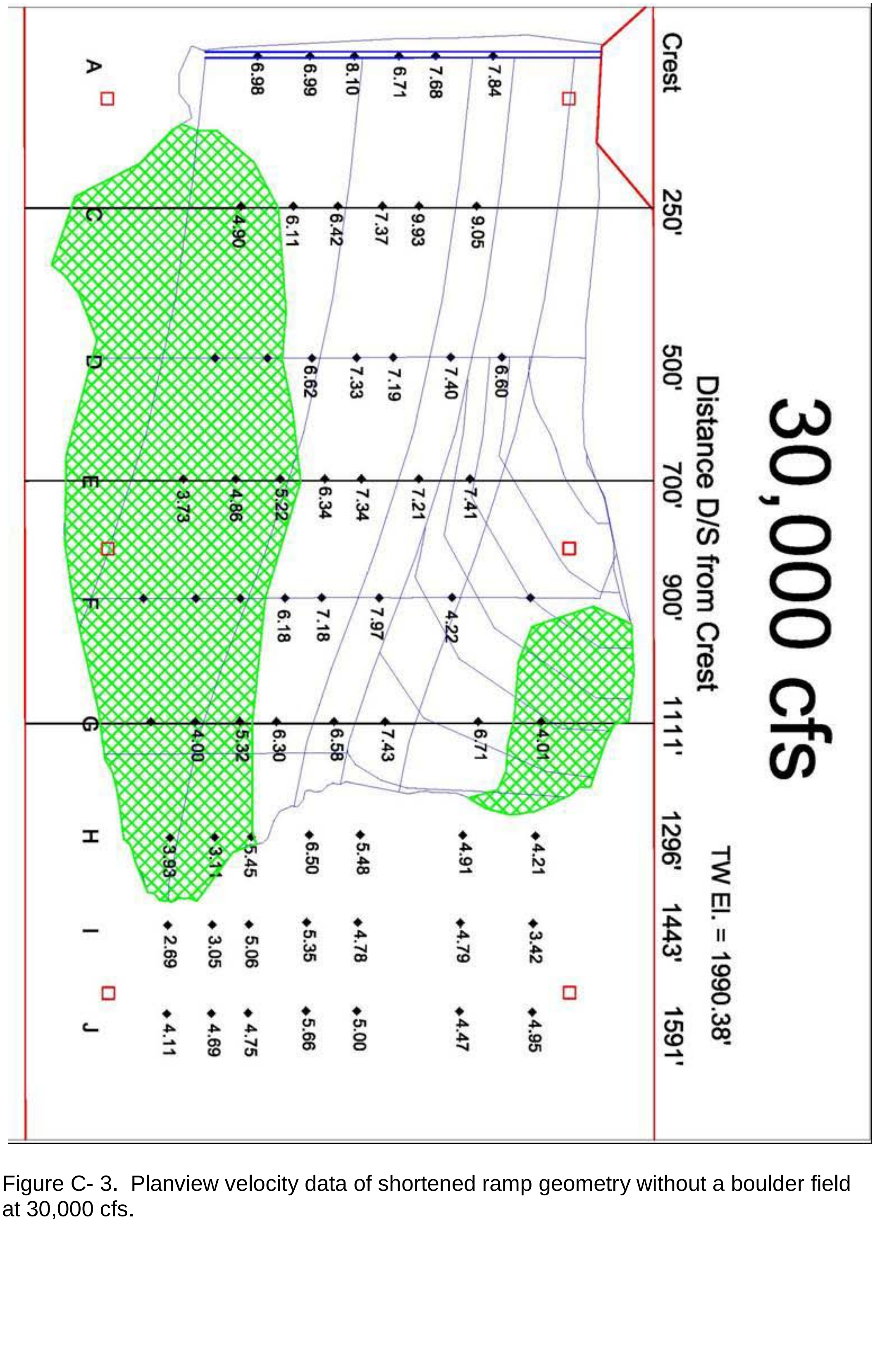

Figure C- 3. Planview velocity data of shortened ramp geometry without a boulder field at 30,000 cfs.

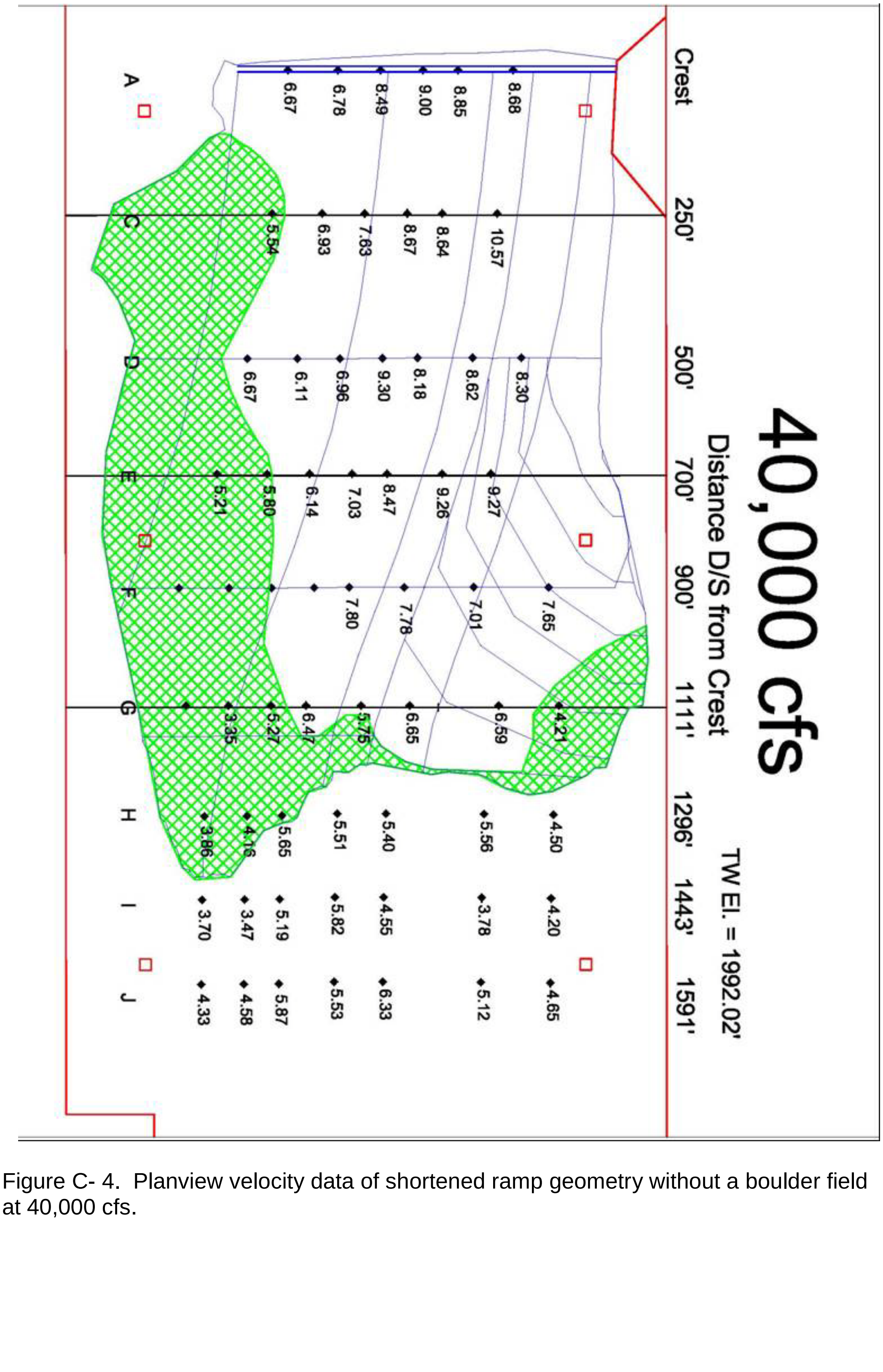

Figure C- 4. Planview velocity data of shortened ramp geometry without a boulder field at 40,000 cfs.

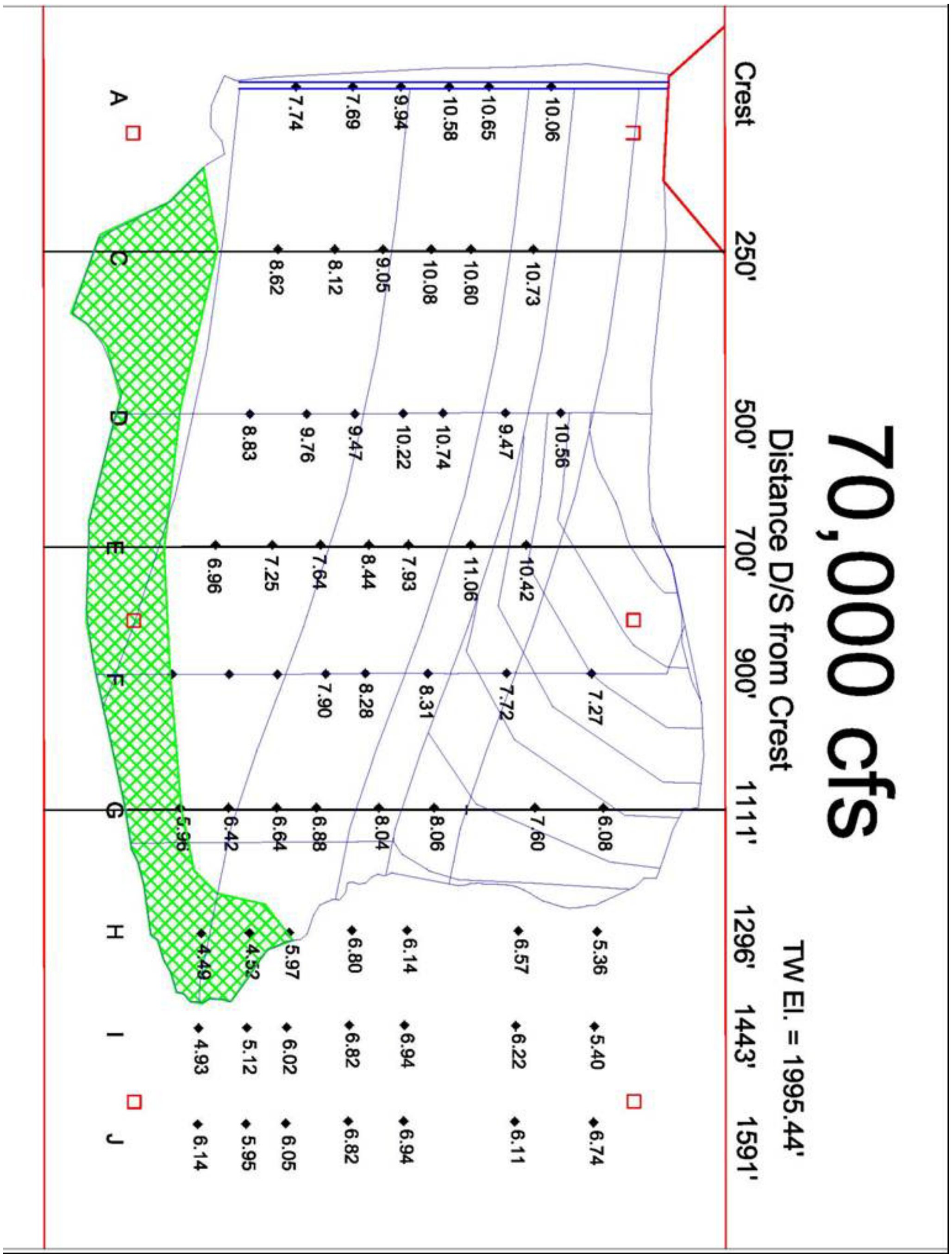

Figure C- 5. Planview velocity data of shortened ramp geometry without a boulder field at 70,000 cfs.

Appendix D

Model Construction Photographs

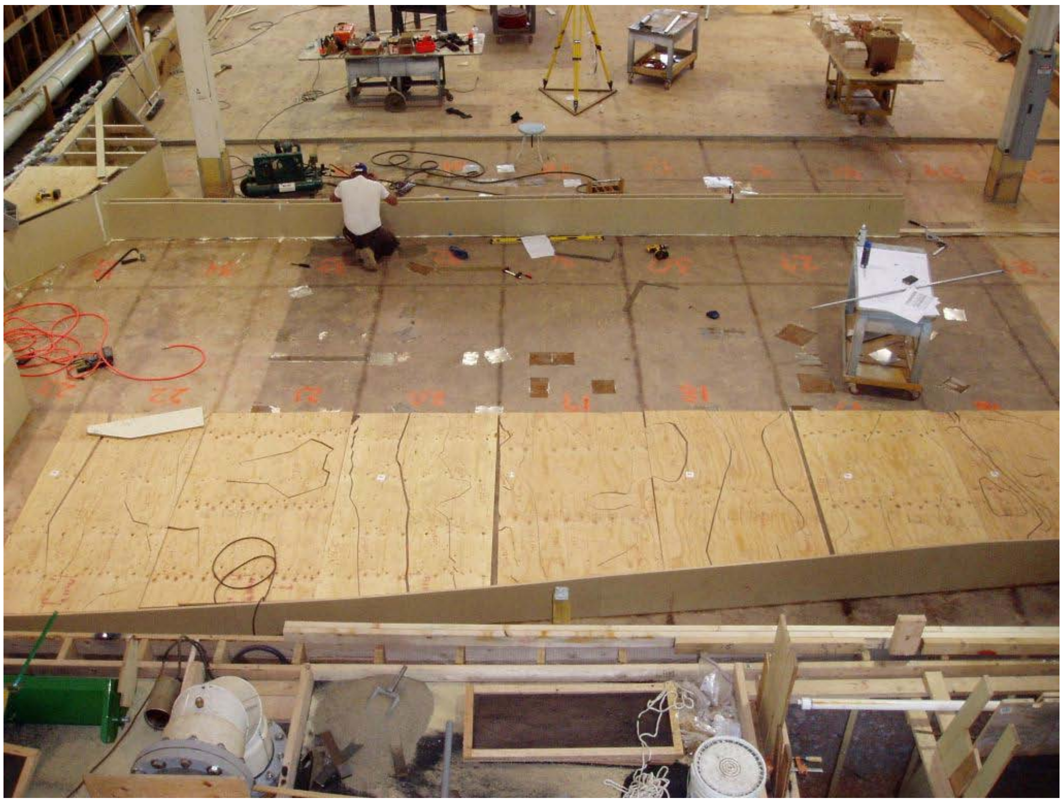

Figure D- 1. Initial phase of model construction of diversion weir and upstream topography.

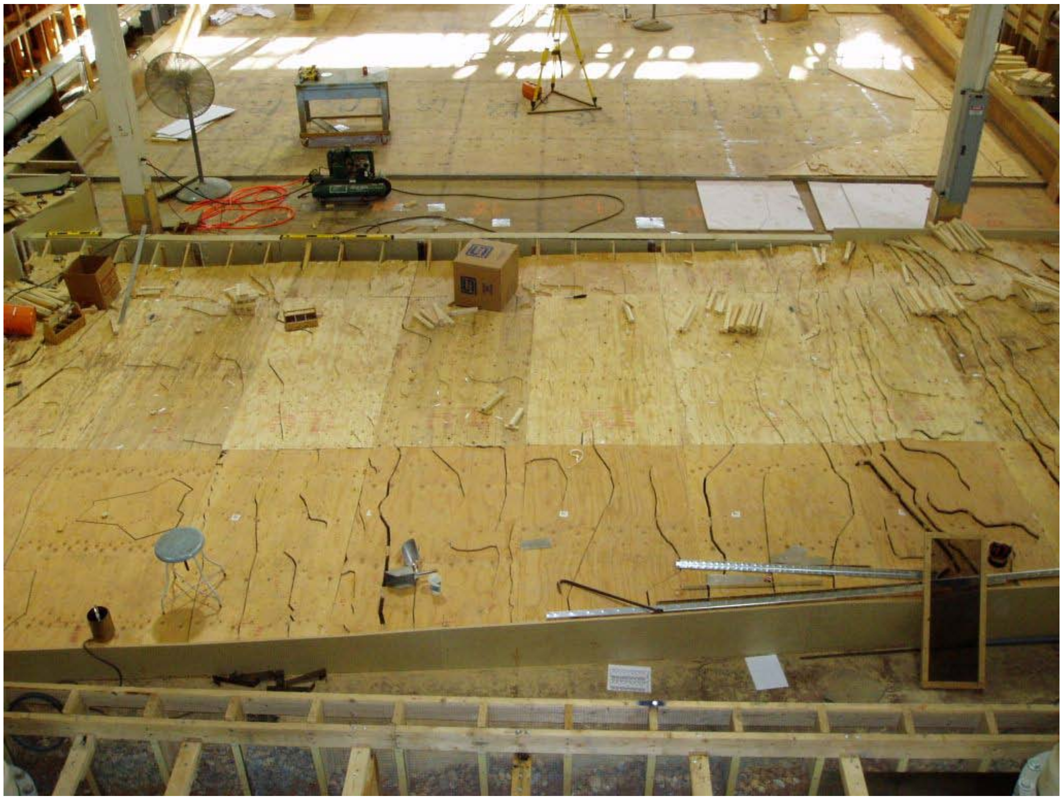

Figure D- 2. Upstream topography meeting diversion weir.

Figure D- 3. Concrete layer over upstream topography.

Figure D- 4. Installation of angular rock and breakline templates for model rock ramp.

Flow Scenario Photographs

Figure D- 5. 7,000 ft^3/s flow setting, flowing right to left.

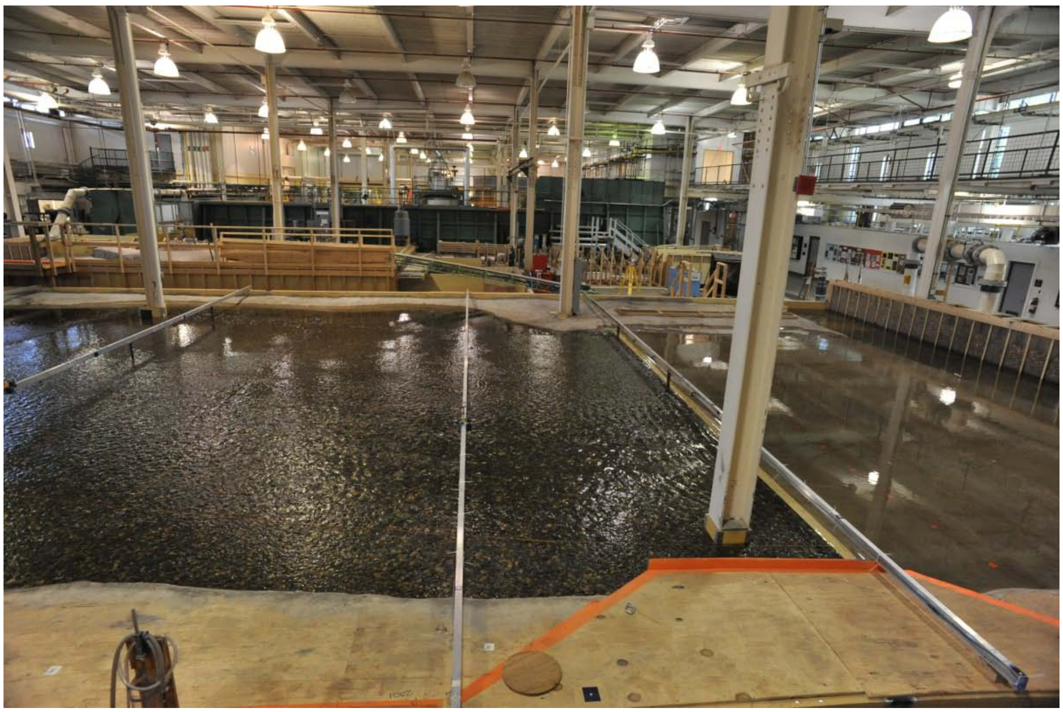

Figure D- 6. 15,000 ft^3/s flow setting, flowing right to left.

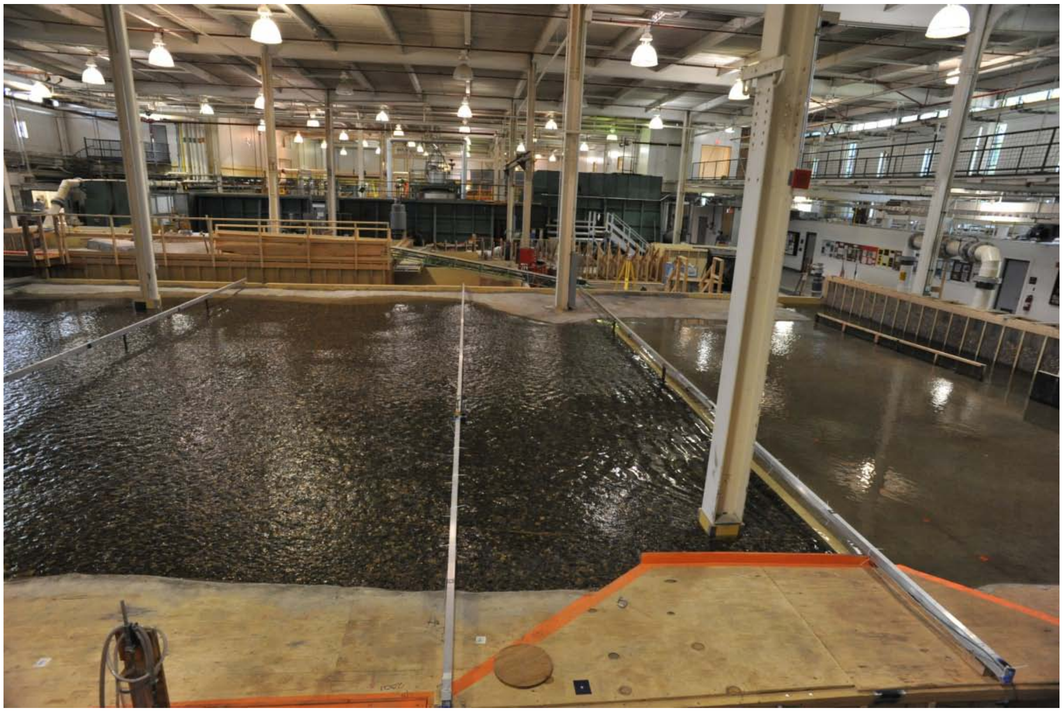

Figure D- 7. 30,000 ft^3/s flow setting, flowing right to left.

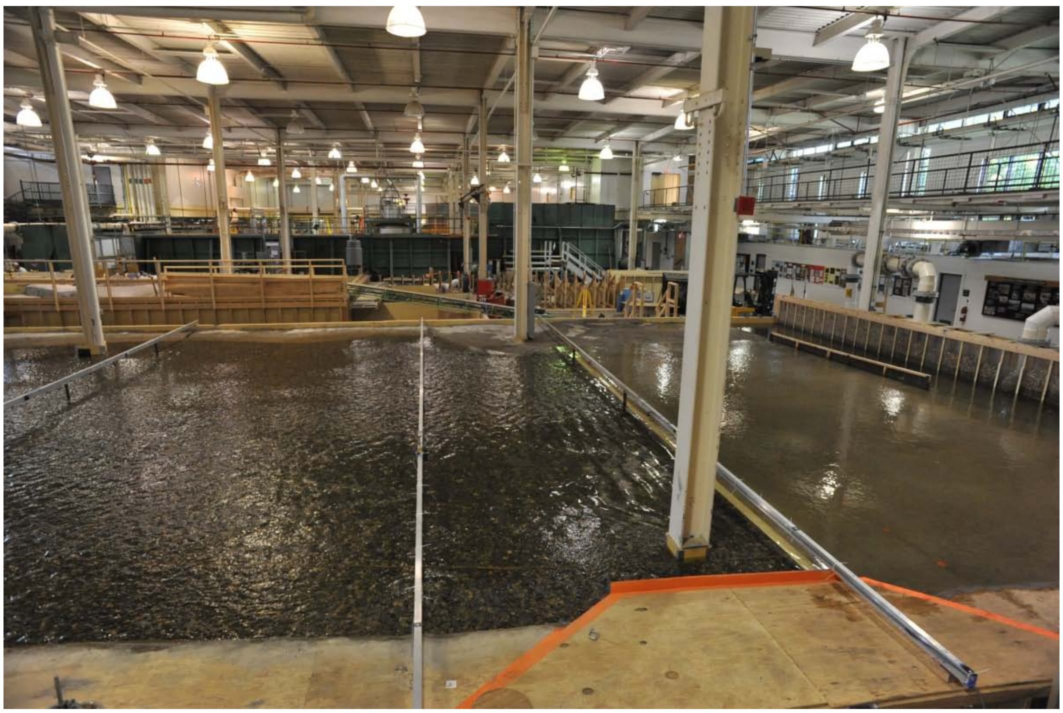

Figure D- 8. 40,000 ft^3/s flow setting, flowing right to left.

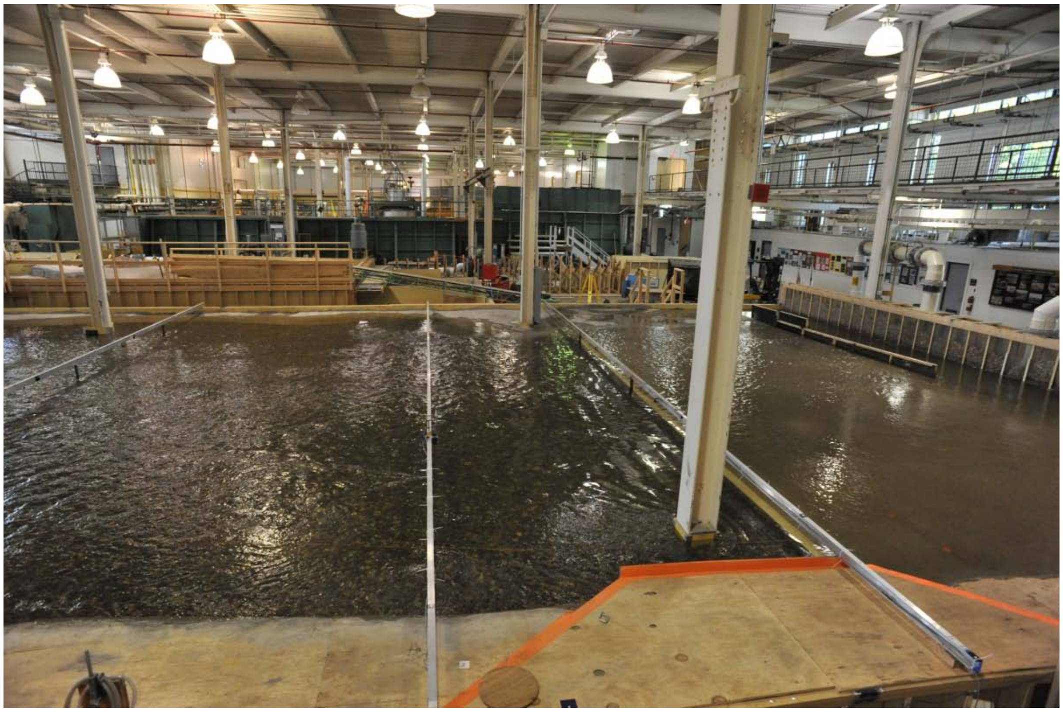

Figure D- 9. 70,000 ft^3/s flow setting, flowing right to left.

Shortened (C2) Ramp Photographs

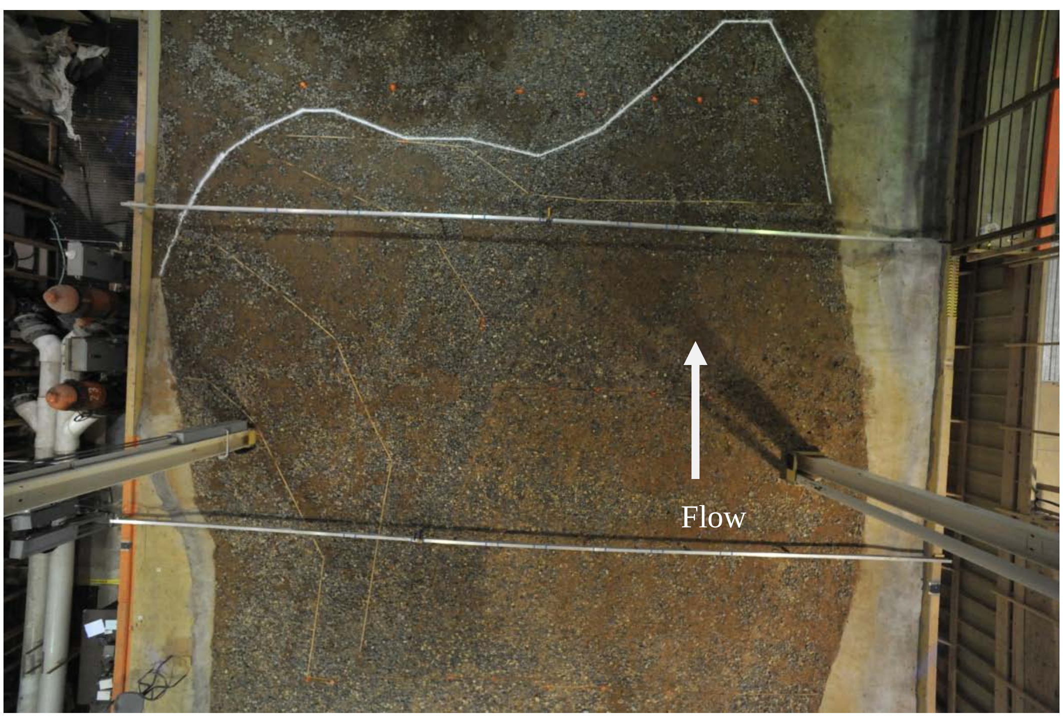

Figure D- 10. Shortened ramp modification to physical model.

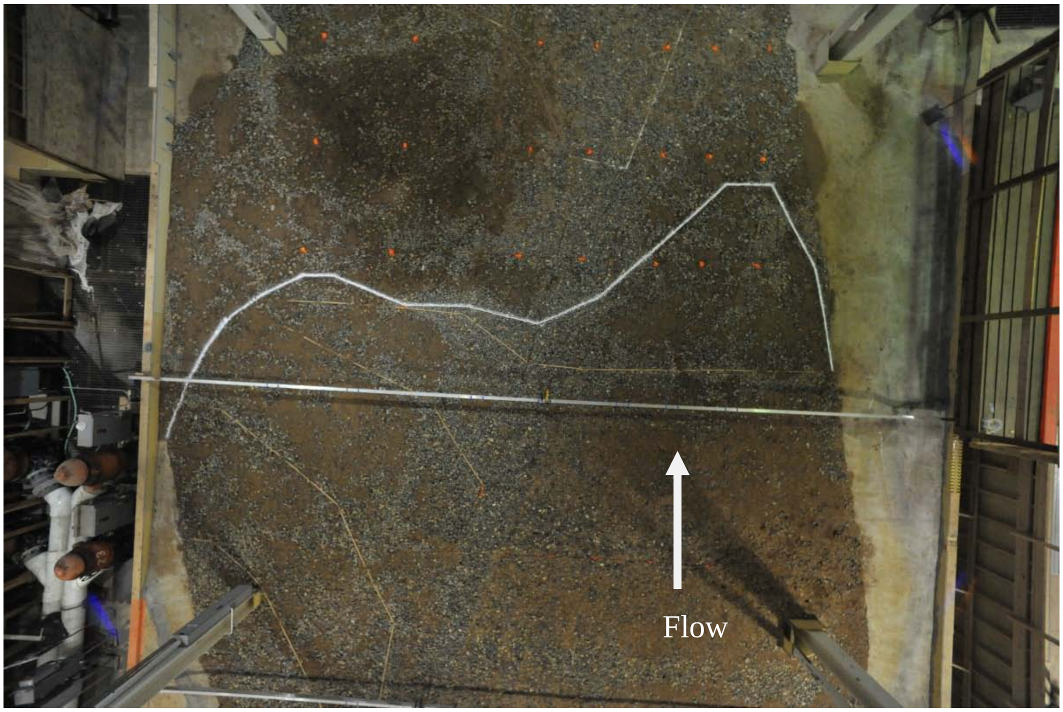

Figure D- 11. Shortened ramp modification to physical model.

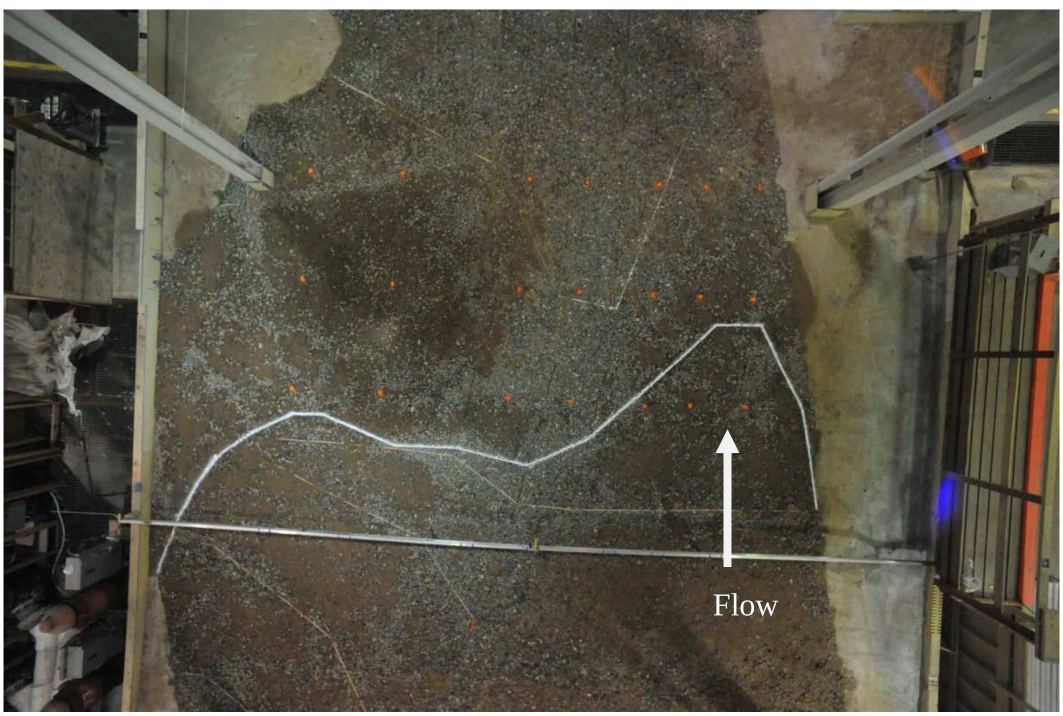

Figure D- 12. Shortened ramp modification to physical model, orange dots indicate velocity measurement locations with FlowTracker.