APPENDIX E:

Crystal River Hydraulic Modeling Report

Crystal River Hydraulic Modeling Report
Garfield and Pitkin Counties, Colorado

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RRO Project No. 11.CO29.001
December, 2015

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December 3rd, 2015

Introduction

The Crystal River flows west and north from its headwaters in the central Elk Range of the Rocky Mountains approximately 40 miles to the confluence with the Roaring Fork River near Carbondale, CO. Managing instream flows throughout the section of the Crystal River from Redstone, CO to Carbondale, CO has been the focus of an ongoing conversation pertaining to the future of the Crystal River. The river primary uses are for agricultural water rights which draw flows from the river and the maintenance of instream flows for aquatic habitat and recreation opportunities. Efforts are ongoing to explore options balancing the riparian health with water users.

A section of the Crystal River extending approximately eight miles upstream of the Roaring Fork River confluence was examined to evaluate alternatives for instream flow maintenance. The channel geometry (i.e. bed slope, sinuosity, and width to depth ratio) remains relatively consistent through the entire project. Aerial photography was examined over time to draw information pertaining to the stability and geomorphic characteristics of the river. Bathymetric survey data were collected and structured into a digital elevation model (surface) of the channel. The produced surface was utilized to investigate hydraulic characteristics within the channel across a variety of flow rates and management scenarios. Numerical models of flow within the Crystal River produced robust hydraulic data capable for evaluation of existing conditions as well as structural modifications associated with a range of alternatives for instream flow maintenance. Data will be incorporated into habitat assessments for various restoration alternatives. This report documents a geomorphic overview, survey data collection, hydraulic model development, and representative results of four instream alternatives.

Site description and morphological assessment

The project reach ranged from the Roaring Fork confluence (39°25’06.89”N, 107°14’10.98”W) to S. Bill Creek Rd (39°19’10.98”N, 107°12’34.63”W). The selected section of the Crystal River was analyzed through aerial imagery from 1993 - 2015 to resolve geomorphic characteristics and trends over time (Google, 2015). Figure 1 provides a site overview of the location of the Crystal River. The selected channel reach has exhibited minimal migration over the duration of the aerial photography record, primarily due to entrenchment within quaternary terraces. Figure 2 illustrates a representative reach of channel in the vicinity of Crystal Bridge Drive exhibiting remnant meandering geometry wherein local areas of interior floodplain develop. The river maintains a moderately steep slope, S_O, of approximately 0.008, an overall sinuosity of 1.2, a width to depth ratio on the order of 35, meander lengths on the order of 1,750 ft, a representative top-width of approximately 140 ft, and a radius of curvature to top-width ratio of approximately 3.5. Quantitative observations of the meander characteristics correspond well with empirical observations of unconfined alluvial channels made by Leopold et al. (1960). The river has been observed as relatively stable in planform over time and the values of the radius of curvature to top-width ratio and sinuosity index indicate a high potential for erosion (Biedenharn et al., 1989; Nanson and Hickin, 1986; Brice 1984). Overall, the channel is classified as a stable, sinuous system confined within a paleo channel with strong potential for erosion and bed load transport.

Figure 1. Crystal River study area vicinity, Google (2015)

Survey data

Survey data were collected within the channel and on the banks of the project reach as illustrated in Figure 2. Data were compiled from various sources including survey work performed by RiverRestoration (RRO) in conjunction with Lotic Hydrological (Lotic). Data were projected in NAD83 Colorado State Plane Central Zone, US Foot. The bathymetric survey data was interpolated to produce a 5-ft grid spacing within the bankfull limits of the channel and a 25-ft spacing on the overbanks. Interpolated data were used to generate a surface of the project reach, illustrated in Figure 3.

Two representative sediment samples were collected in November, 2015 by RRO in the vicinity of Mt Sopris Ranch Rd Bridge (39°22'54.97"N, 107°12'17.61"W). Each sample consisted of 100 randomly selected particles measured along the intermediate axis. Samples were collected upstream of the bridge in a riffle section and downstream in a pool section. Figure 4 details the sediment size distributions at both locations. Table 1 and Table 2 summarize pertinent size classes and gradations for the riffle and pool samples, respectively. The riffle sample was observed to contain a more uniform, cobble distribution ($\sigma = d_{84}/d_{16} = 2.4$) while the pool sample contained coarser large cobble materials with larger variability ($\sigma = 5$).

Figure 2. Crystal Bridge Rd vicinity, meander length, radius of curvature, and top width. Instream survey points and alignment illustrated

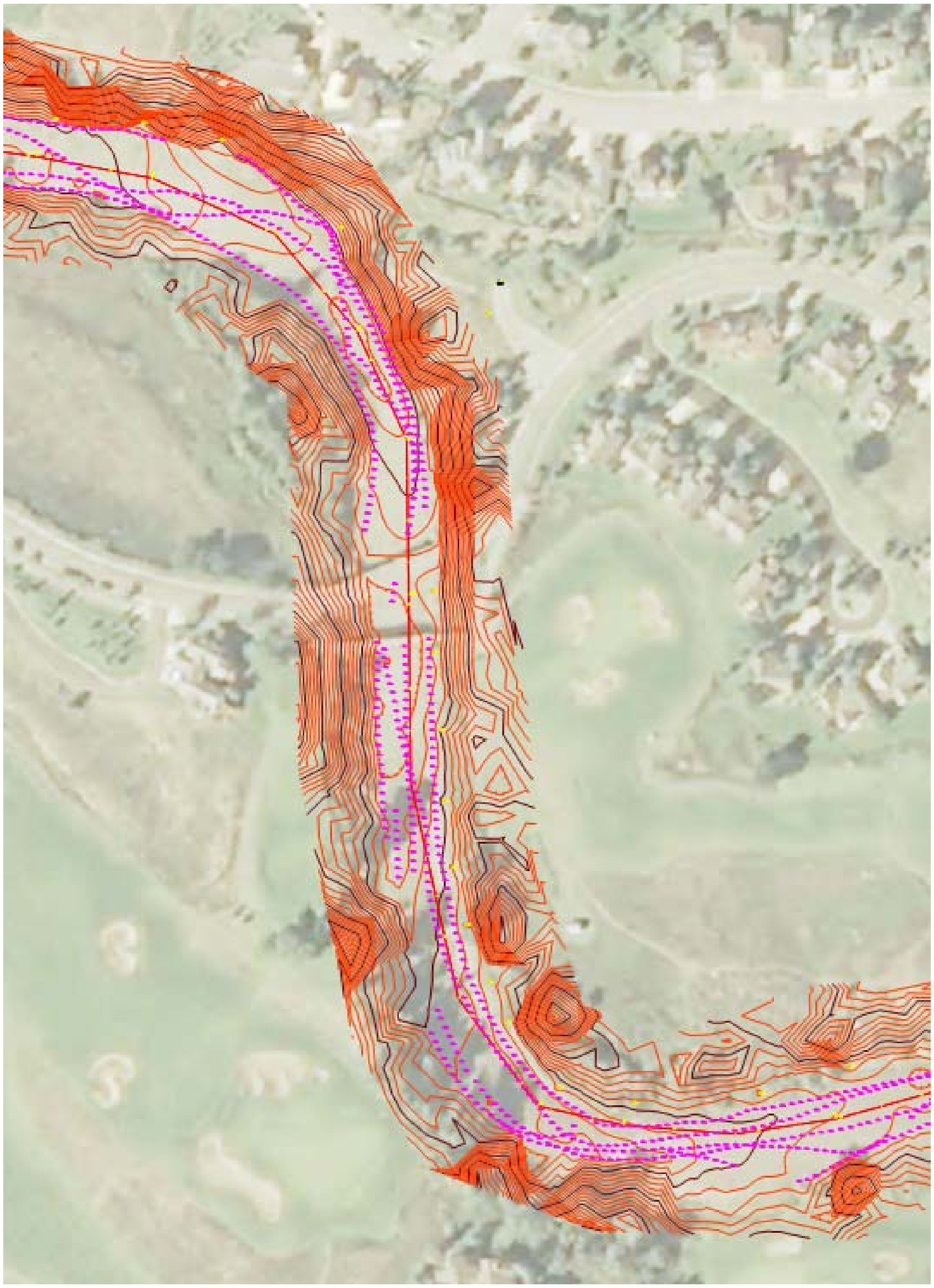

Figure 3. Surface created from survey points, vicinity of Crystal Bridge Rd. Red contours at 1 ft, black at 5 ft; flow direction upwards

Table 1. Sediment sample – Upstream Mt Sopris Street Bridge

Size	Riffle - US Bridge (mm)	Classification
d_{10}	60.96	very coarse gravel
d_{16}	76.20	small cobble
d_{25}	76.20	small cobble

Size	Riffle - US Bridge (mm)	Classification
d_{50}	106.68	small cobble
d_{75}	167.64	large cobble
d_{84}	182.88	large cobble
d_{95}	335.28	small boulder

Table 2. Sediment sample – Downstream Mt Sopris Street Bridge

Size	Pool - DS Bridge (mm)	Classification
d_{10}	60.96	very coarse gravel
d_{16}	60.96	very coarse gravel
d_{25}	91.44	small cobble
d_{50}	137.16	large cobble
d_{75}	228.6	large cobble
d_{84}	304.8	small boulder
d_{95}	548.6	medium boulder

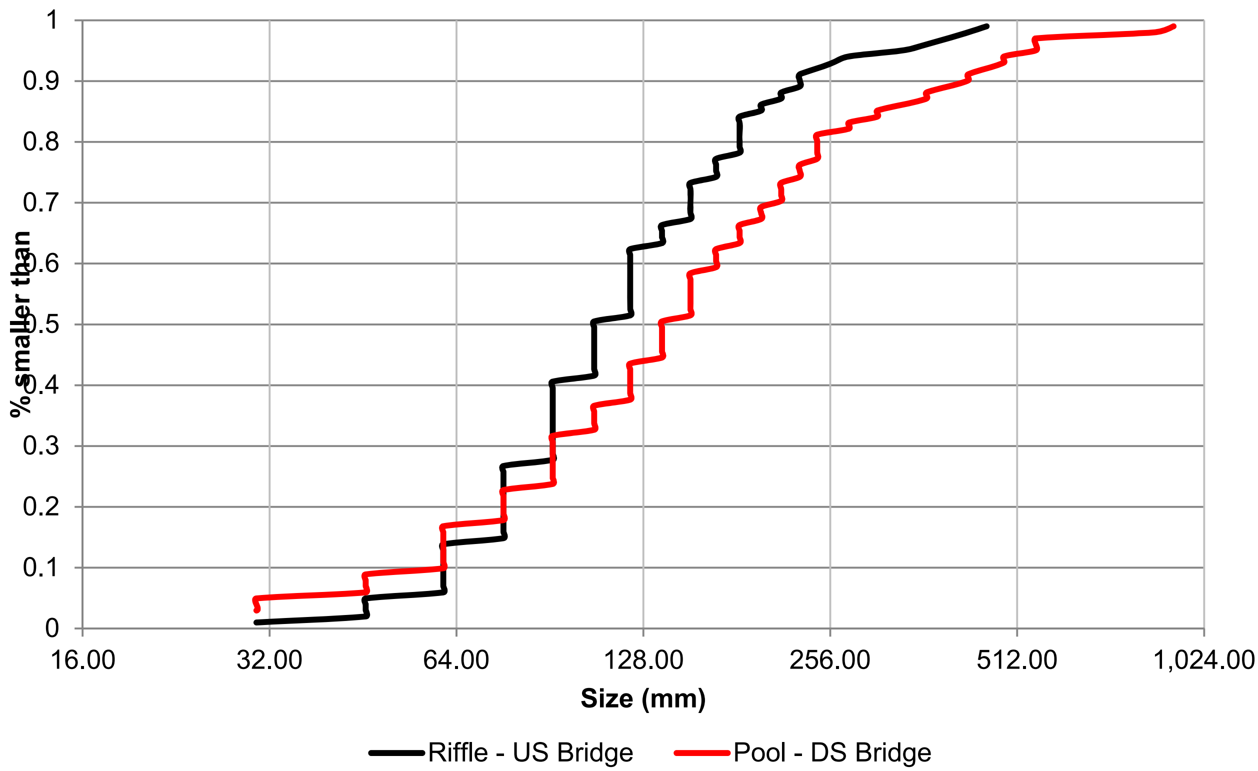

Figure 4. Sediment size distributions within study reach

Hydraulic modeling

Survey data were used to develop a series of hydraulic models to evaluate four configurations within the project reach. A existing conditions configuration was first evaluated over the full eight miles of the Crystal River. Three structural alterations to the channel were then evaluated, including a single A-weir, a designed low-flow habitat channel (LFHC), and a representative channel length of proposed river restoration structures from Wildland Hydrology (2014). The goal of the hydraulic model was to investigate habitat parameters within the channel which may vary significantly across a channel cross section. In order to simulate existing and proposed habitat effects within the project reach, a two-dimensional hydraulic model was utilized to generate hydraulic parameters at a variety of flows and channel configurations.

Two-dimensional hydraulic model

The Sedimentation and River Hydraulics – 2D River Flow Model (SRH-2D) was developed by the United States Bureau of Reclamation to implicitly solve finite volume fluid dynamics simulations for a variety of open-channel environmental applications (Lai, 2010; Reclamation, 2008). The code has been thoroughly validated and verified in field applications and has widespread use in the scientific and engineering community. The program solves the two-dimensional Navier-Stokes equations of fluid motion on regular or irregular meshes. For all modeling applications, a two-equation κ-ε turbulence model was implemented.

Grid layout, boundary conditions, and initial conditions are dependent upon each application and must be specified. Required inputs are detailed for each application of SRH-2D to the Crystal River. Grid formation was achieved though the implementation of SMS v11.2.10 (Aquaveo, 2015). Output parameters available for all simulations include the location of each grid cell (x,y,z) and associated flow depth, water-surface elevation, Froude number, velocity direction and magnitude, boundary shear stress, turbulent dissipation rate, and turbulent kinetic energy.

Existing conditions

The existing conditions model was used to investigate the full project reach, from the Roaring Fork confluence to S. Bill Creek Rd. The interpolated survey data surface was manipulated to generate the numerical solution mesh and no structural modifications to the channel were included. The model was purposed for examination of habitat conditions as a function of the quantity of water in the existing channel and may serve to approximate benefits of irrigation water releases to the main channel.

Grid spacing for the existing conditions model considered computational restrictions for performing simulations on the large reach (approximately 8 miles) of river. The chosen mesh size allowed for simulation times on the order of a few days while providing resolution to appropriately estimate habitat hydraulics throughout the channel reach. Typically, grid size is based upon independence criteria; resolution is incrementally increased until successive differences are negligible. For the existing conditions, overbank resolution was set at a 30-ft grid size and instream resolution was set at a 5-ft grid size. The instream resolution matched the interpolated grid surface provided by Lotic. Figure 5 illustrates detail of the existing conditions mesh.

Boundary conditions for open-channel hydraulic models require a specified downstream water-surface elevation and upstream inflowing discharge. Downstream boundary conditions for the existing conditions model assumed normal depth at river station 360 ft upstream of the Roaring Fork confluence. Normal depth is defined as the condition of a river system without any upstream or downstream control on the flow; the channel form and roughness dictates the water surface elevation. Normal depth may be calculated using the relationship of Equation 1 (Chow, 1959).

$$Q \big/ A(y_N) = \frac{\phi}{n}\left[\frac{A(y_N)}{P(y_N)}\right]^{2/3} S_O^{\;1/2} \tag{1}$$

where:

Q = volumetric flow rate;

A = cross-sectional flow area;

φ = coefficient = 1.486 SAE;

n = Manning roughness coefficient;

P = cross-sectional wetted perimeter; and

y_N = normal flow depth.

For a given cross-sectional geometry, there exists a unique function of A and P with the flow depth, y. The cross-sectional geometry was extracted at 360 ft upstream of the Roaring Fork confluence and regression functions were fitted to approximate $A(y)$ and $P(y)$ with coefficients of determination exceeding 0.99. Inserting functions to Equation 1 and solving for y_N allows for the generation of a downstream boundary rating curve. Values of n for the calculation of normal depth were set at a calibrated 0.05 based on one-dimensional model results at the flow rate during bathymetric survey. The value of S_O was set at 0.008, determined from surveyed elevation data located near the cross section. Table 3 summarizes the boundary conditions for the existing conditions model along with other evaluated configurations. Table 4 provides locations of the downstream boundary for all evaluated models.

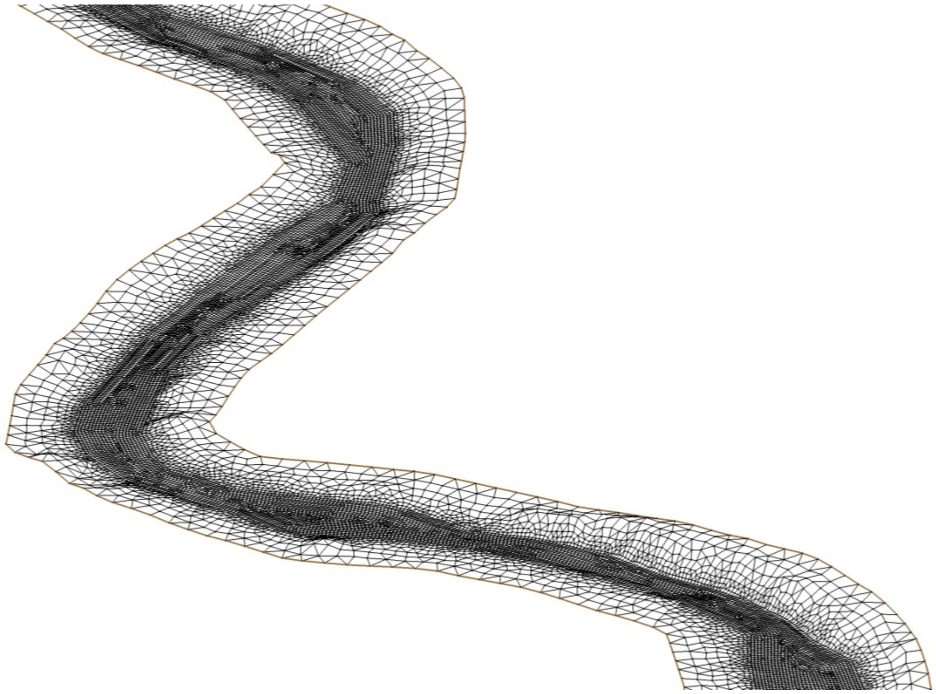

Figure 5. Existing conditions mesh detail

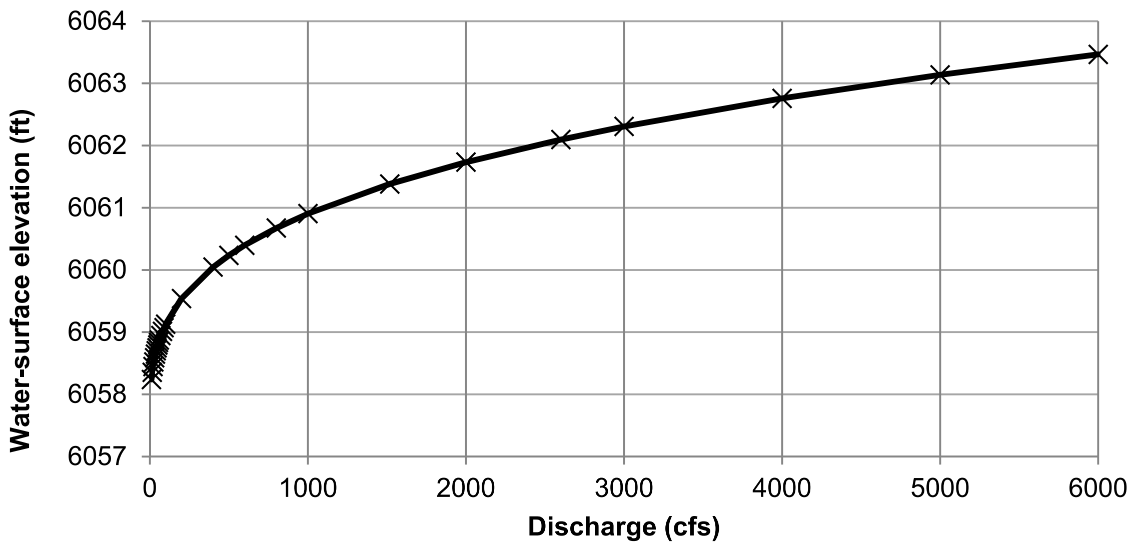

Figure 6. Existing conditions model downstream boundary rating curve

Table 3. Flow rates and boundary conditions evaluated for numerical models

		Downstream boundary elevation (ft)		
Discharge	Existing conditions	A-weir	LFHC	W. Hyd (2014)
5	6058.07	6190.79	6200.28	6213.10
10	6058.24	6190.98	6200.38	6213.19
15	6058.35	6191.11	6200.46	6213.27
20	6058.45	6191.21	6200.52	6213.31
25	6058.52	6191.29	6200.57	6213.36

Discharge	Existing conditions	Downstream boundary elevation (ft) A-weir	LFHC	W. Hyd (2014)
30	6058.59	6191.36	6200.62	6213.40
35	6058.65	6191.43	6200.66	6213.44
40	6058.70	6191.49	6200.70	6213.47
45	6058.75	6191.54	6200.74	6213.50
50	6058.79	6191.59	6200.78	6213.54
55	6058.84	6191.64	6200.81	6213.57
60	6058.87	6191.68	6200.84	6213.59
70	6058.95	6191.76	6200.90	6213.64
80	6059.01	6191.84	6200.96	6213.69
90	6059.07	6191.90	6201.01	6213.74
100	6059.13	6191.97	6201.05	6213.78
200	6059.54	6192.42	6201.43	6214.11
300	n/a	n/a	6201.71	6214.36
400	6060.05	6192.99	6201.94	6214.57
500	6060.23	6193.20	6202.13	6214.75
600	6060.40	6193.38	6202.31	6214.91
800	6060.67	6193.69	6202.62	6215.20
1000	6060.90	6193.95	6202.89	6215.44
1518	6061.38	6194.49	6203.48	6215.97
1650	n/a	6194.60	6203.60	6216.09
2000	6061.73	6194.88	6203.92	6216.38
2600	6062.10	6195.29	6204.40	6216.82
3000	6062.31	6195.52	6204.69	6217.08
4000	6062.76	6196.03	6205.32	6217.67
5000	6063.14	6196.45	6205.86	6218.17
6000	6063.47	6196.82	6206.35	6218.62

Table 4. Location of downstream boundaries, from Roaring Fork confluence

Configuration	DS Boundary Location (ft)
Existing conditions	359.99
A-weir	15994.32
LFHC	17230.27
Conceptual Restoration Plan	19418.82

The existing conditions hydraulic model was simulated until the solution converged to a steady state. Values of n were iterated over the full model at the discharge where survey data were collected (Q = 1,518.06 cfs) to minimize difference between field and model simulations. A value of n = 0.04 provided the best results compared to field data. All runs were conducted at uniform surface roughness. Figure 7 illustrates representative model output for velocity magnitudes from the existing conditions model at 100 cfs and 1,000 cfs.

A-weir hydraulic modeling

Structural alterations to the project reach affect flow depth, velocities, and other hydraulics influencing habitat and recreational objectives. River-spanning rock weirs are a form of structural alteration and have been installed in a variety of applications where grade control is desired, yet a traditional dam-type drop structure is not desired. Rock weirs may benefit habitat through increasing hydraulic diversity from scour depths, backwater, and interstitial flows (Roni et al., 2002). Despite increasing popularity for instream installations, rock weir design guidelines for predictable hydraulic and habitat effects are still not fully realized. The United States Bureau of Reclamation (Reclamation) provides a summary of available structure design recommendations and emphasizes the inclusion of hydraulic modeling during design (Gordon et al., 2015). An application of a rock-weir structure type, the A-weir, was simulated within the Crystal River to ascertain hydraulic effects.

The A-weir is a river spanning rock weir with arms extending at an angle downstream from a crest set perpendicular to the flow direction. An additional crest exists at approximately the midpoint of the structure length in the downstream direction, creating two hydraulic drops across the structure. Figure 8 illustrates a schematic from Rosgen (2006) detailing an A-weir cross-vane. River flows encountering the structure are backwatered behind the structure, converge through the throat, and form a jet which scours the downstream pool.

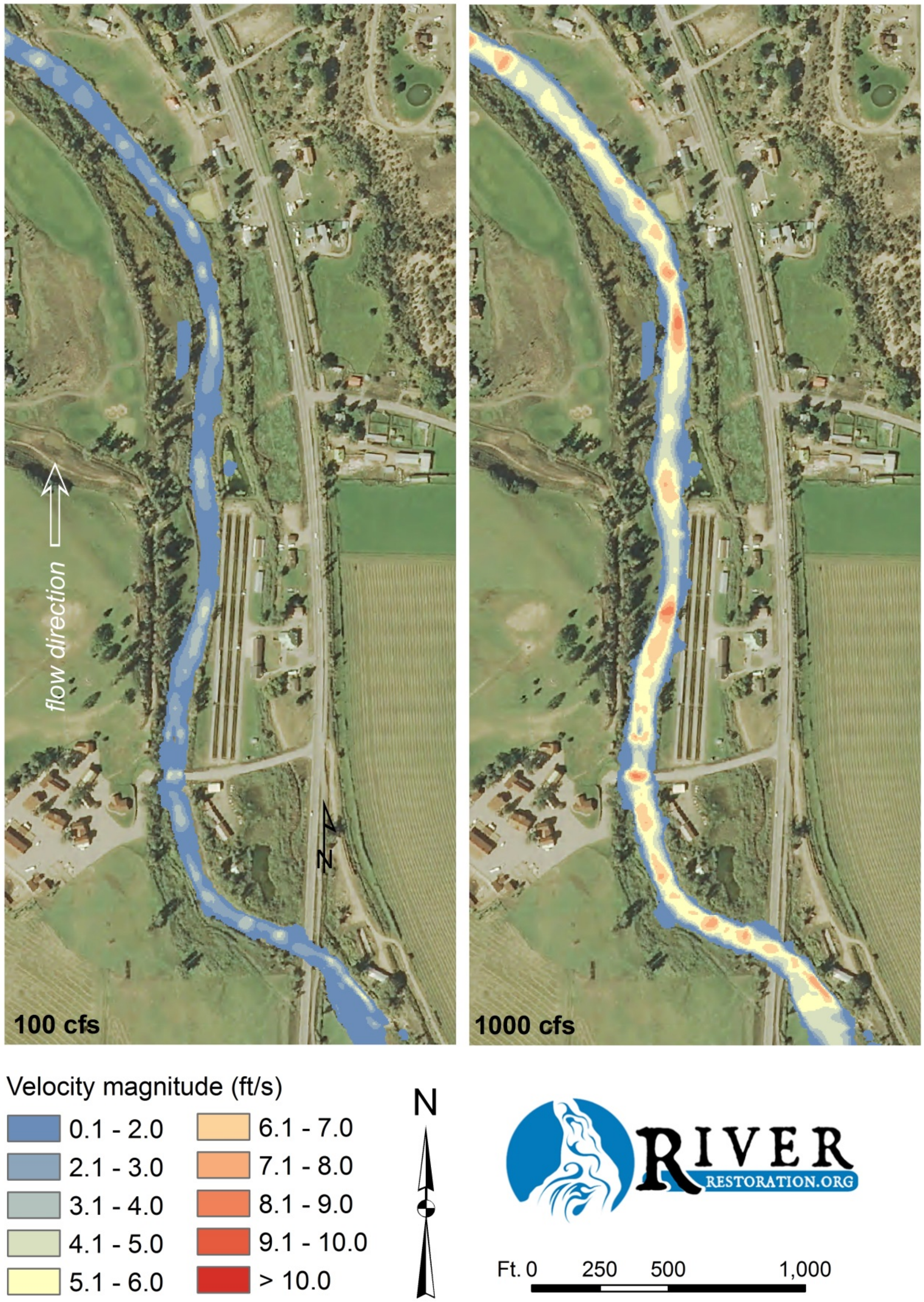

Figure 7. Existing conditions model velocity magnitude results, near Crystal River Hatchery

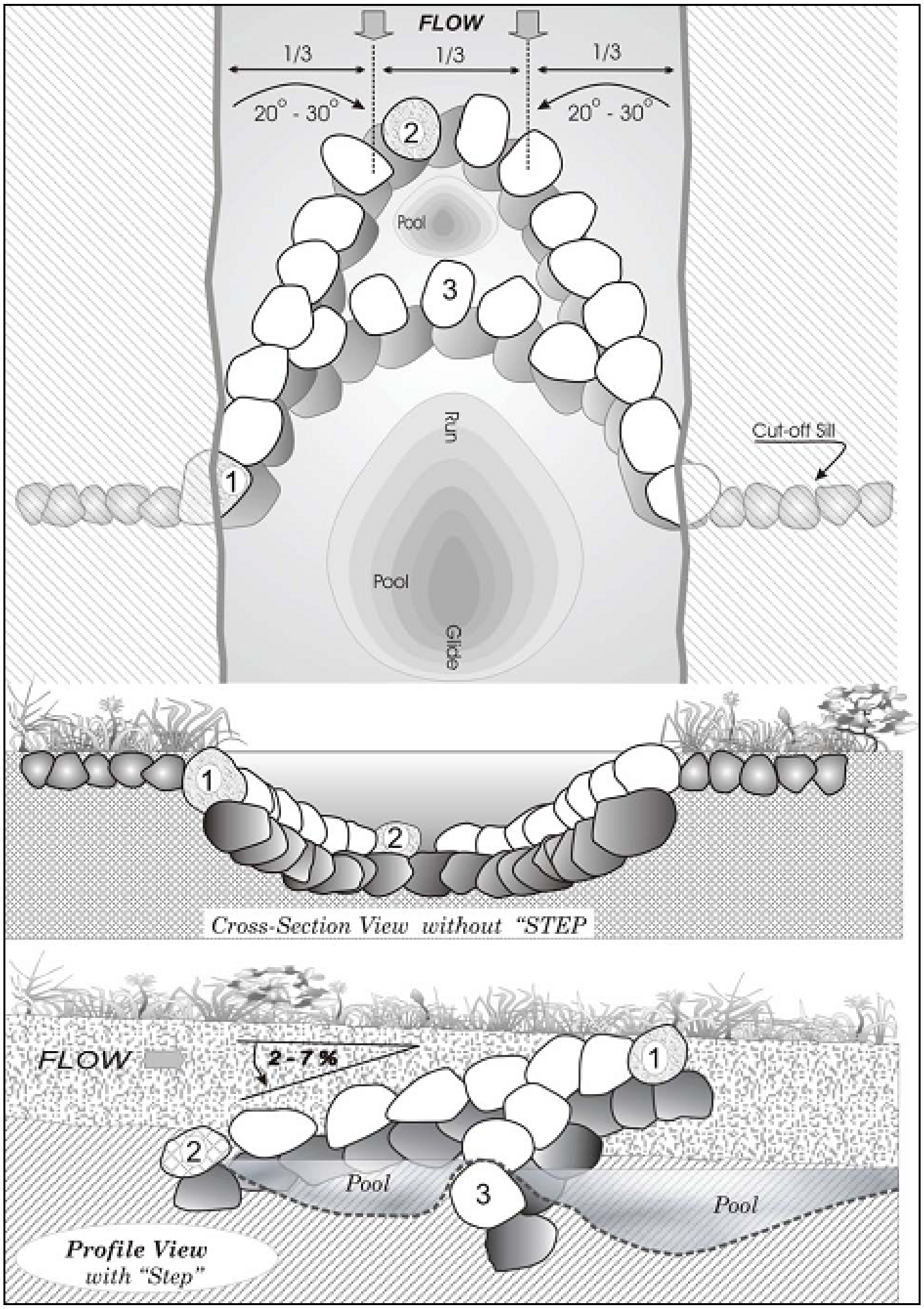

Figure 8. A-weir schematic (Rosgen, 2006)

Specifics of the hydraulics pertaining to A-weirs have been researched in recent years, primarily through physical model studies. Using a comprehensive set of laboratory data, Thornton et al. (2011) developed a set of stage discharge relationships describing the backwater effects from A-weirs as a function of weir crest geometry. The same dataset was used by Scurlock et al. (2012) to quantify equilibrium scour patterns. Scour geometry characteristics were described by Pagliara et al. (2013). Backwater and equilibrium scour hydraulics are important for habitat as they directly influence depths and velocities. The efficacy of two-dimensional modeling in replicating A-weir hydraulics has not been fully addressed in the literature. To ensure model accuracy for applications to the Crystal River, the dataset of Thornton et al. (2011) and Scurlock et al. (2012) was further investigated to determine the level of accuracy predicted by two-dimensional hydraulic models.

Laboratory experiments were conducted at Colorado State University on a series of rock A-weirs installed in a 16-ft wide gravel-bed flume subjected to flow rates up to 40 ft^3/s. Figure 9 illustrates the A-weir used for data analysis under testing conditions. Comprehensive topography and velocity data were available to develop and compare two-dimensional hydraulic simulation results. A numerical simulation surface was created from LiDAR data with downstream boundary conditions obtained from measured water-surface elevations. The A-weir evaluated corresponded to configuration A/c/3 from Scurlock et al. (2012). Grid independence was found to occur at a spacing of 0.25 ft within the main channel and 0.1 ft near the structure arms; subsequent halving of the grid spacing produced a global root-mean square deviation of 0.005 ft. Roughness was iterated and converged at a value of n = 0.04 throughout the full channel based on water-surface comparisons to laboratory data.

A-weir laboratory simulation velocity and flow depth results are illustrated in Figure 10. Water-surface elevations were predicted by the numerical model within 1% of the average flow depth, verifying the capabilities of accurately representing backwater. Velocities within the laboratory were not as well represented as flow depths, with error on the order of 19% of the average velocity recorded in the flume. Flow across rock weirs is highly three dimensional and contains vertical hydraulics not represented with two-dimensional models. Velocity discrepancies arise directly from the inability of the two-dimensional model to capture complex vertical hydraulics. However, results do provide velocity resolution at the accuracy appropriate to estimate relative habitat effects.

Scour geometry from Scurlock et al. (2012) was examined to determine the most accurate way of representing anticipated equilibrium patterns for the structures modeled in the Crystal River. Figure 11 illustrates a typical scour geometry taken from a laboratory evaluation of the A-weir previously analyzed. Notable differences were observed between actual scour patterns compared to the A-weir schematics of Figure 8; maximum scour formed near the junction of the weir arms and cross-bar with a dual thalweg extending downstream. Maximum scour depth and geometry for simulated A-weirs in the Crystal River used findings from the laboratory to accurately represent bed morphology.

Two-dimensional hydraulic simulations of laboratory A-weir structures indicated that application of a hypothetical A-weir to a representative reach of the Crystal River would provide confident quantitative estimations of changes to hydraulics. A geomorphically representative reach of the Crystal River upstream of Crystal Bridge Road was selected to model the hydraulic influence of an A-weir installation. The selected site for the A-weir corresponds to a structure proposed by Wildland Hydrology (2014), located immediately downstream of a diversion for an irrigation channel. The modeled stretch of reach spanned from river station 15,994.32 ft to 18,644.82 ft upstream of the Roaring Fork confluence, with the modeled grid extents illustrated in Figure 12. Downstream boundary conditions were established using methods previously discussed. Downstream water-surface elevations and all associated flow rates evaluated for the A-weir are summarized in Table 4.

Figure 9. Laboratory A-weir under bankfull testing conditions

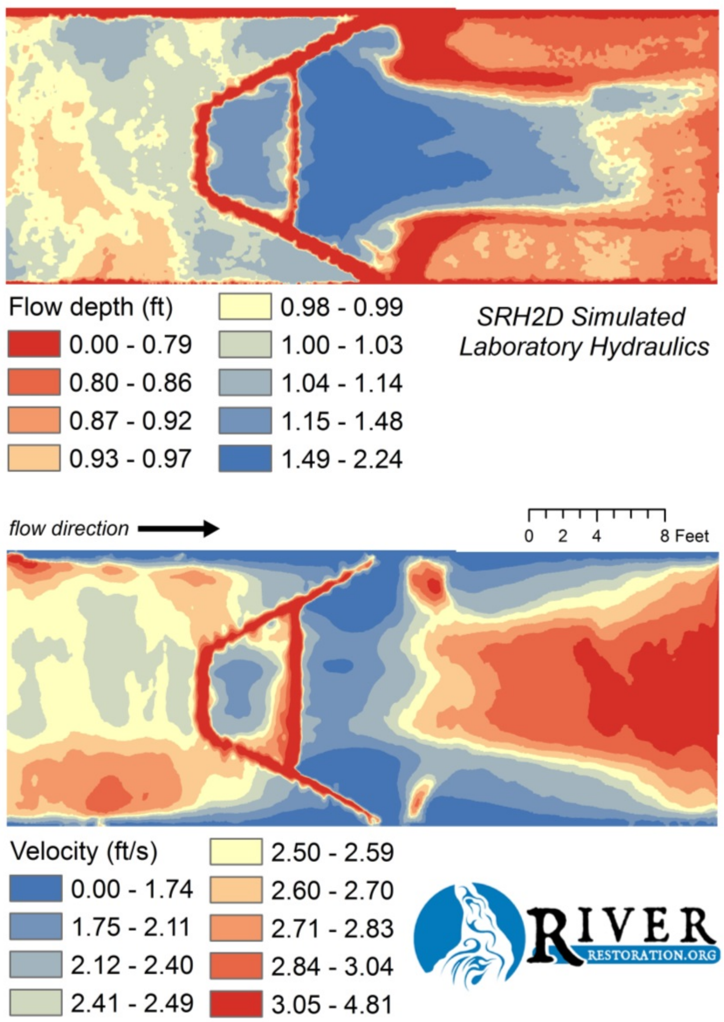

Figure 10. Two-dimensional hydraulic simulation results, laboratory A-weir

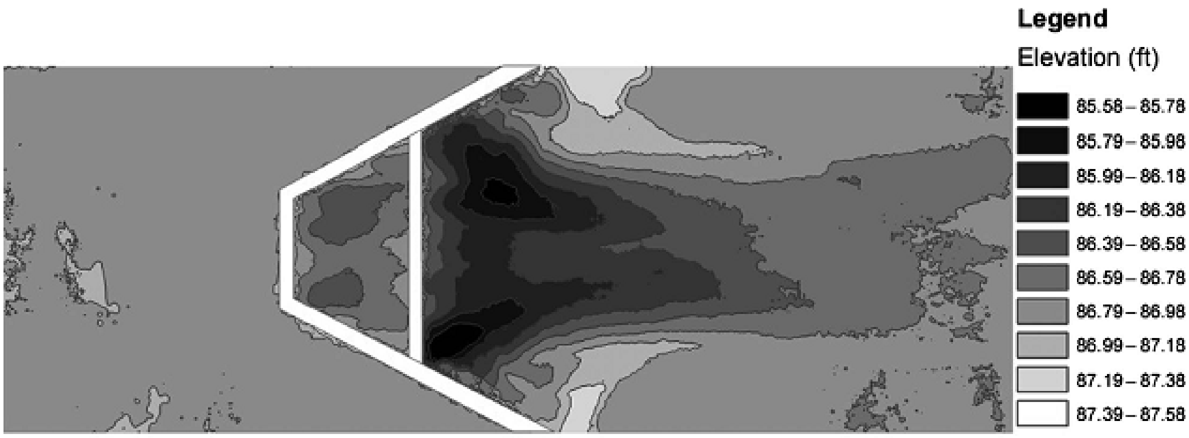

Figure 11. Typical A-weir equilibrium scour formation, Scurlock et al. (2012)

Figure 12. A-weir structure modeling reach in Crystal River

The modeled A-weir structure was designed to adhere to geometric ranges recommended by Rosgen (2006) while maximizing backwater according to relationships from Thornton et al. (2011). Optimized backwater was desired to maximize the area of hydraulic influence for habitat comparisons. The crest height of the designed A-weir was set at 0.8 ft above the channel bed, recommended as the maximum for fish habitat concerns from Reclamation (2015). The crest throat was set at one-third of the bankfull top width, the planimetric arm angle was set at 30°, and arms extended up to the tie-in elevation at 3.41° for a maximum downstream arm distance of approximately 70 ft.

Given the comparative purpose between habitat hydraulics of the model simulations, two models of the simulated reach were conducted; one with, and one without a structure. Additional existing conditions modeling allowed for near-direct comparison of data locations instead of relying on the coarser resolution of the full existing conditions model. Grid independence was found to occur at a spacing of 5 ft at the bankline, transitioning to 0.5 ft at the structure crest and arms. Reduction of the grid to 2.5 ft and 0.25 ft, respectively, had no discernible effect in water-surface elevations (<1%). Roughness values of n = 0.04 were applied uniformly throughout the model following conclusions from the laboratory comparisons and existing conditions model results. Models were run at various flow rates and boundary conditions until the solution reached steady-state equilibrium.

Representative model velocity magnitudes for the A-weir existing conditions and structure runs are provided in Figure 13. Figure 14 illustrates the velocity difference of the structure conditions to the existing conditions. The A-weir was observed to reduce velocities upstream of the structure crest due to backwater effects and through the structure reach through energy dissipation and losses through the increased flow depths of the scour pool. Velocities through the scour pool would be expected to have a higher velocity jet at the bottom of the pool and the two-dimensional model results may be lower than expected by approximately 20%. Significant acceleration of the flow is noted over the structure crest. A range of influence was defined where the absolute difference in depth-averaged velocity exceeded 0.10 ft/s (approximately 5% of the channel-averaged velocity magnitude). The range of influence of the A-weir at 100 ft^3/s was measured at approximately 120 ft upstream and 150 ft downstream, or 1.7 and 2.1 times the structure length, respectively.

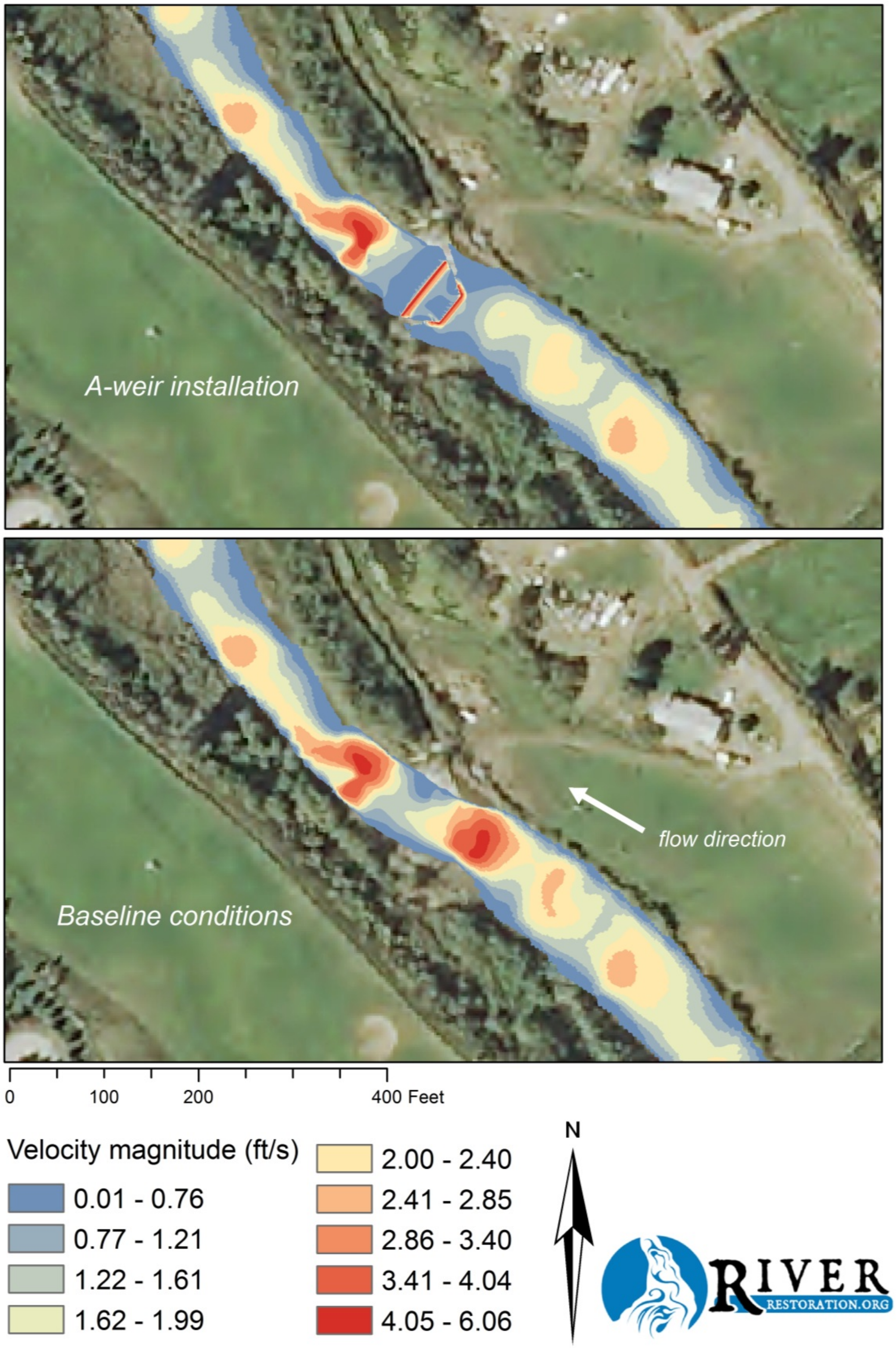

Figure 13. A-weir structure and existing conditions results, 100 cfs

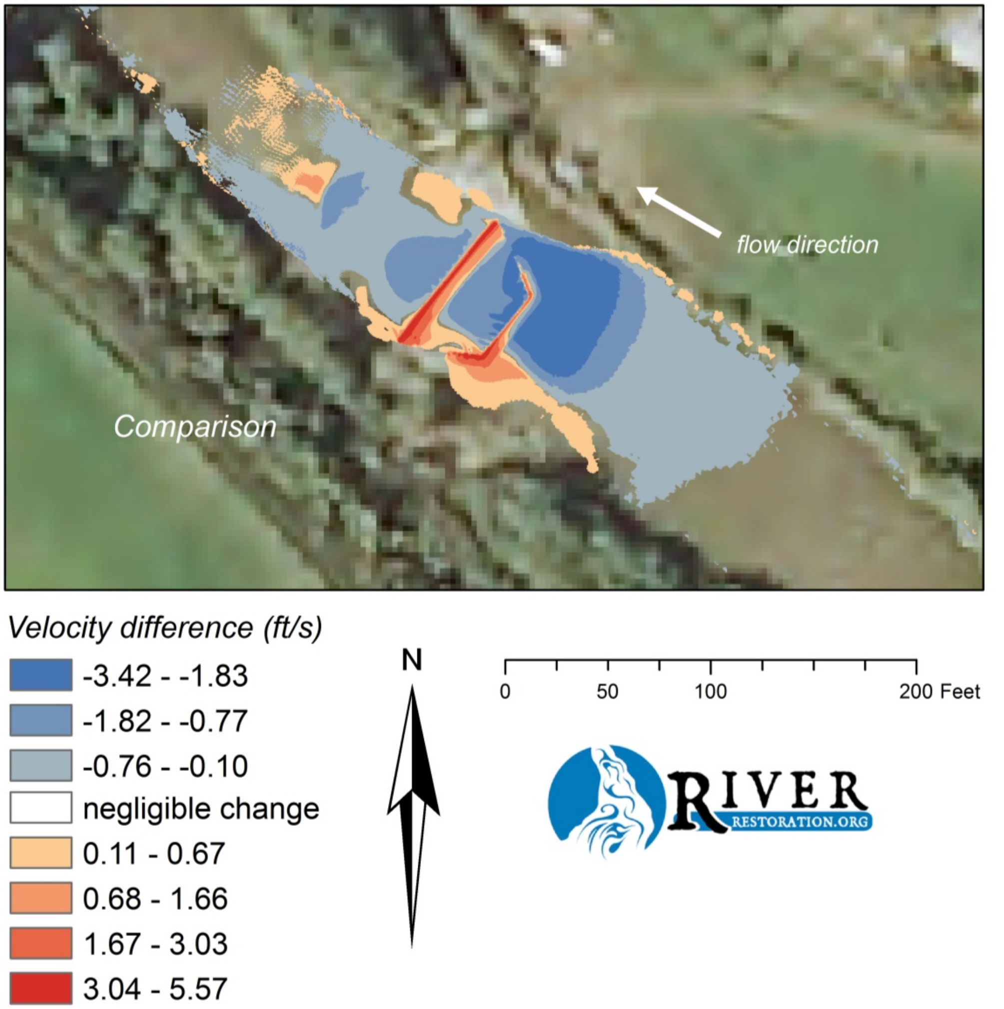

Figure 14. A-weir structure to existing conditions velocity difference, 100 cfs. Displayed are the extents of influence

Low-flow habitat channel (LFHC) modeling

The LFHC is a structural design option to convey all flows below a threshold into a dredged thalweg or connected side channel. Flows within the LFHC would be optimally designed to meet habitat criteria at all flows below an overtopping threshold. Limited information on specific habitat criteria were available at the time of design; therefore, the LFHC was designed based on assumption for desired aquatic habitat. Results presented correspond to one of many options for the configuration of the LFHC.

Selected discharges for the design of the LFHC were 40 ft^3/s and 100 ft^3/s. The design flow of 40 ft^3/s corresponds to the lowest flow rate within the channel where habitat may be prudently augmented and is representative of a low flow scenario. Overtopping discharge of 100 ft^3/s corresponds to the expected habitat maintenance flowrate without structural alternatives (Lotic, personal communication). A hydraulic channel was designed given the discharge range to meet habitat criteria of a minimum 1.0 ft of flow depth, no hydraulic drop within the channel exceeding 0.5 ft, and all structure inverts submerged by tailwater elevation.

The LFHC was designed as a trapezoidal, dredged, and armored channel placed on river left (west) of the main Crystal River channel. Hydraulic design of the LFHC considered intermittent placement of rock arches to create lower velocities and backwater to meet habitat criteria. A rock arch is slightly different from rock weirs (i.e. A-weir) in that the planimetric angle exceeds the 30° maximum specified in Figure 8. The LFHC geometry was specified with a bottom width of 10 ft, a maximum depth of 2 ft, and sideslopes at 1*V*:3*H*. Rock arches were designed with a crest height of 1.0 ft, crest width of 3.0 ft, a throat width at one-third of the LFHC top-width, and with arms extending upwards to the overtopping waterline. Backwater from the designed rock arch was approximated using equations from Thornton et al. (2011) and the structure design was iterated until the upstream water-surface elevation was 1.5 ft at 40 ft^3/s. Structure spacing was determined from the distance between the downstream structure crest and upstream intersection of the backwatered water-surface elevation slope and minimum habitat flow depth. Structures were spaced at a channel distance of 167 ft from the crest midpoint. Figure 15 provides a detail of the water-surface elevation downstream and upstream of the rock arch structures.

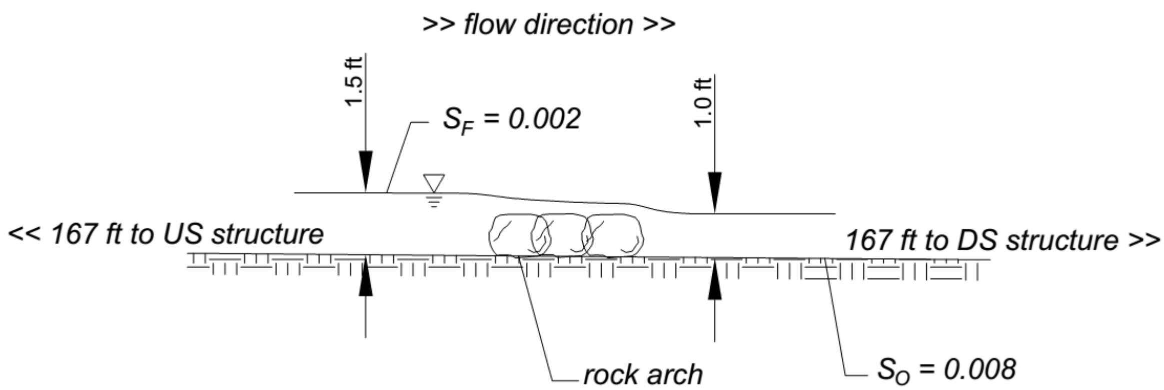

Figure 15. Profile view of LFHC design at rock-arch structure

The LFHC was modeled in a representative reach of the Crystal River upstream of the Crystal Bridge Road. A existing conditions configuration and structure configuration were evaluated for the reach for direct comparison. Scour downstream of the rock arches was modeled as two-times the rock-weir crest following U-weir scour geometries observed by Scurlock et al. (2012). Figure 16 details the two-dimensional model surface used for simulations, illustrating the trapezoidal dredged channel and three rock-arch structures. Mesh sizing was noted as grid independent at 1.0 ft at the structure crests, 3.0 ft within the LFHC and main channel, and 5.0 ft otherwise. Roughness values were set at a constant n = 0.04. Downstream boundary conditions were determined at a cross section located 17,230.27 ft upstream of the Crystal River confluence with the Roaring Fork using methods previously discussed. Boundary conditions and all flow rates evaluated for the LFHC are provided in Table 4.

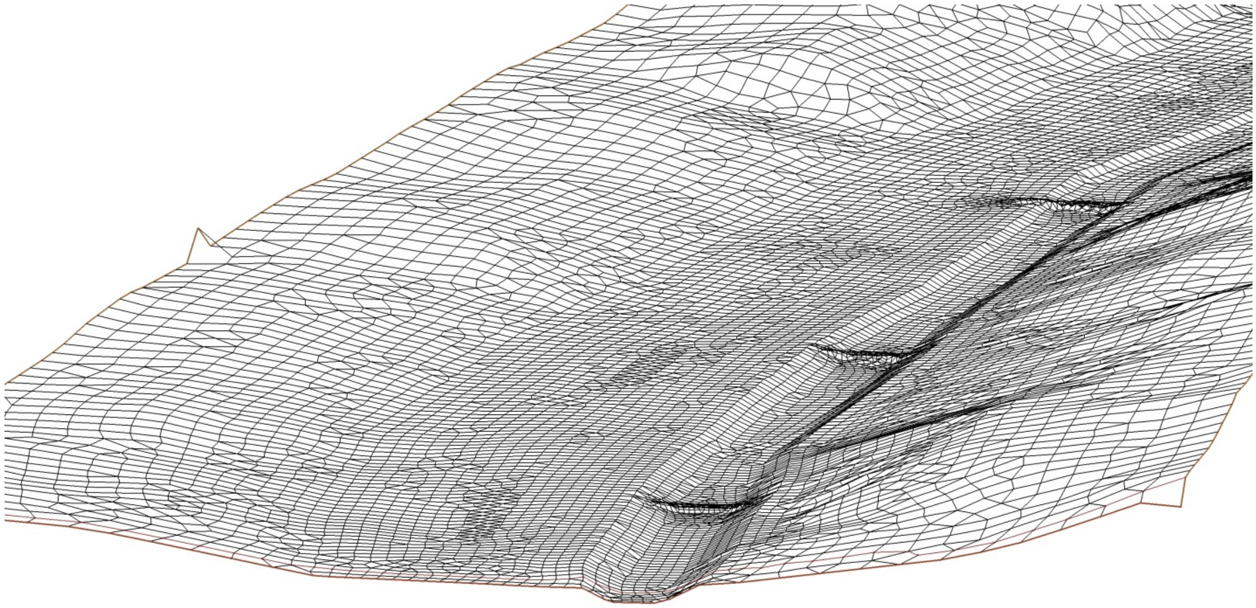

Figure 16. LFHC simulation mesh

Figure 17 illustrates a representative spatial cycle of simulated LFHC flow depths at 40 ft^3/s and 100 ft^3/s. Flow-depth distributions would periodically repeat for each upstream structure addition. At the low-flow design discharge, the two-dimensional results matched hydraulic design, with flow depths backwatered to 1.5 ft gradually decreasing to 1.0 ft immediately downstream of the next structure in the series. At flows exceeding 100 ft^3/s, the LFHC was observed to be overtopped. Results indicate that the LFHC has the potential for design optimization to a variety of habitat hydraulic parameter ranges if provided.

Long-term structural stability of the LFHC would be dependent upon material sizing and bed-load transport dynamics within the channel. Sediment analysis was performed to evaluate the long-term structural stability of the LFHC and maintenance requirements. The Crystal River is primarily a bed load system with armoring to larger size classes. Such systems begin to entrain increasingly large bed load sizes at larger discharges. Stability concerns include the settling of materials transported from the main channel to the lower elevation of the LFHC resulting in long-term aggradation, or large, channel forming events effectively mobilizing and reshaping overall channel form.

A unique relationship exists between sediment size classifications and boundary shear stress required for transportation. At a critical shear stress, τ_C, for a given particle classification, the substrate is at the threshold for mobilization (Julien, 2006). Simulated boundary shear stress values from the two-dimensional models were examined for the LFHC and main channel across the full range of flows to determine the discharge which transports the sediment sizes found in the Crystal River as detailed in Table 1 and Table 2.

Table 5 details sediment sizes, values of τ_C for each size, and the discharge observed to produce values within the LFHC and main channel. Numerical results indicated that the conveyance and boundary shear stress are primarily concentrated within the LFHC at lower flow rates, with sediment transport occurring at lower discharges for very coarse gravel and small cobble than within the main channel. Mobile substrates in the main channel will likely remain mobile within the LFHC, indicating that long-term aggradation is not anticipated as a significant concern. Models indicated that at higher flows, large cobbles to boulders are transported within the main channel and LFHC simultaneously. Channel-wide bed transport would trend the LFHC to a river-wide uniform bottom profile as it presently exists. While the flood event necessary to effectively reform the LFHC occurs with low probability (approx. 2% annual chance), materials transported are on the order of the mean grain size within the channel (d_{50}) which indicates that mobility may occur on a more regular basis. Therefore, model results for boundary shear stress may be non-conservative; the LFHC may trend towards channel-wide uniformity at flow rates lower than 5,000 ft^3/s. Structural stability of the LFHC option would require construction from large boulders and routine inspection and adaptive maintenance.

Table 5. Sediment transport exceedance discharges for LFHC and main channel

	τ_C	Q for τ_C exceedance	
Classification	lb/ft²	LFHC	Main
very coarse gravel	0.54	60	500
small cobble	1.11	800	1518
large cobble	2.32	5000	5000
small boulder	4.66	>6000	>6000
medium boulder	9.34	>6000	>6000

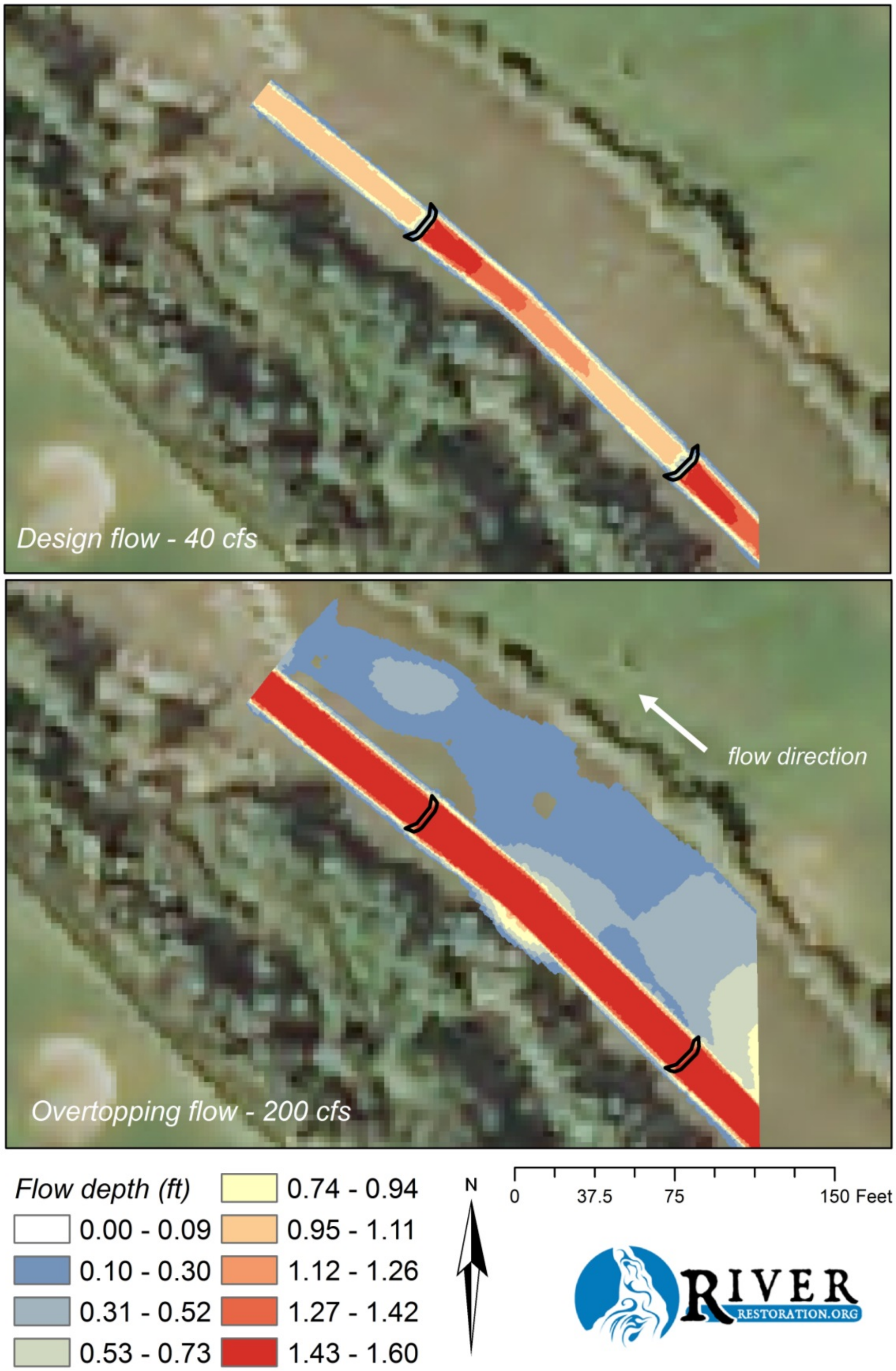

Figure 17. LFHC representative flow depth results

Wildland Hydrology (2014) conceptual restoration design

Wildland Hydrology (2014) produced a conceptual restoration design plan for a section of the Crystal River located between approximately the Crystal Bridge Rd and Mt Sopris Ranch Rd Bridge (river station 11,160 ft and 26,000 ft upstream of the Roaring Fork confluence). The plan details locations of A-weirs and J-hooks along with other, less intensive bank stabilization and instream additions such as woody debris and boulder clusters. The J-hooks are transverse instream structures which guide flow away from the outer-bank and promote bank stabilization and habitat enhancement. Figure 18 details a schematic of a J-hook from Rosgen (2006). Three segments of the channel were identified in Wildlife Hydrology (2014). For the purposes of habitat hydraulic modeling, the upstream reach, entitled "Beat 3" was selected as a representative application of the type of conceptual restoration indicated for construction within the Crystal River. Following structural type and location recommendations from Wildlife Hydrology (2014), structures were designed, overlaid on the existing conditions survey data, and hydraulically modeled to predict hydraulic influence at a variety of flow rates.

An aerial schematic of Beat 3 was overlaid on aerial imagery and the existing surveyed existing conditions surface as illustrated in Figure 19. The spatial limits of Beat 3 were extracted from the existing surface and a downstream boundary was computed at a distance of 19,419 ft upstream of the Roaring Fork confluence. Boundary conditions and discharges used to evaluate the Beat 3 reach are provided summarized in Table 4.

A existing conditions model was established with a grid sizing of 3.0 ft in channel, 5.0 ft overbank, and 15.0 ft at the flow extents which served to provide direct comparison data and to generate necessary design data for the structures. As indicated by Rosgen (2006), design criteria for A-weirs and J-hooks are dependent on the bankfull-flow elevation. The bankfull-flow elevation is the water surface at which the stream begins to overtop the banks and is indicated by observable topographic and vegetation gradients in a natural system. A bankfull discharge of 1,650 ft^3/s was determined from the 1.5-year return interval flood based on a Log-Pearson distribution of annual peak flood data from an upstream stage-discharge gage (USGS, 2015). Bankfull-flow waterlines produced from the numerical model corresponded well with surveyed top-of-bank shots from the field. The bankfull-flow elevation was extracted for design at each location of a proposed A-weir or J-hook indicated by Wildland Hydrology (2014).

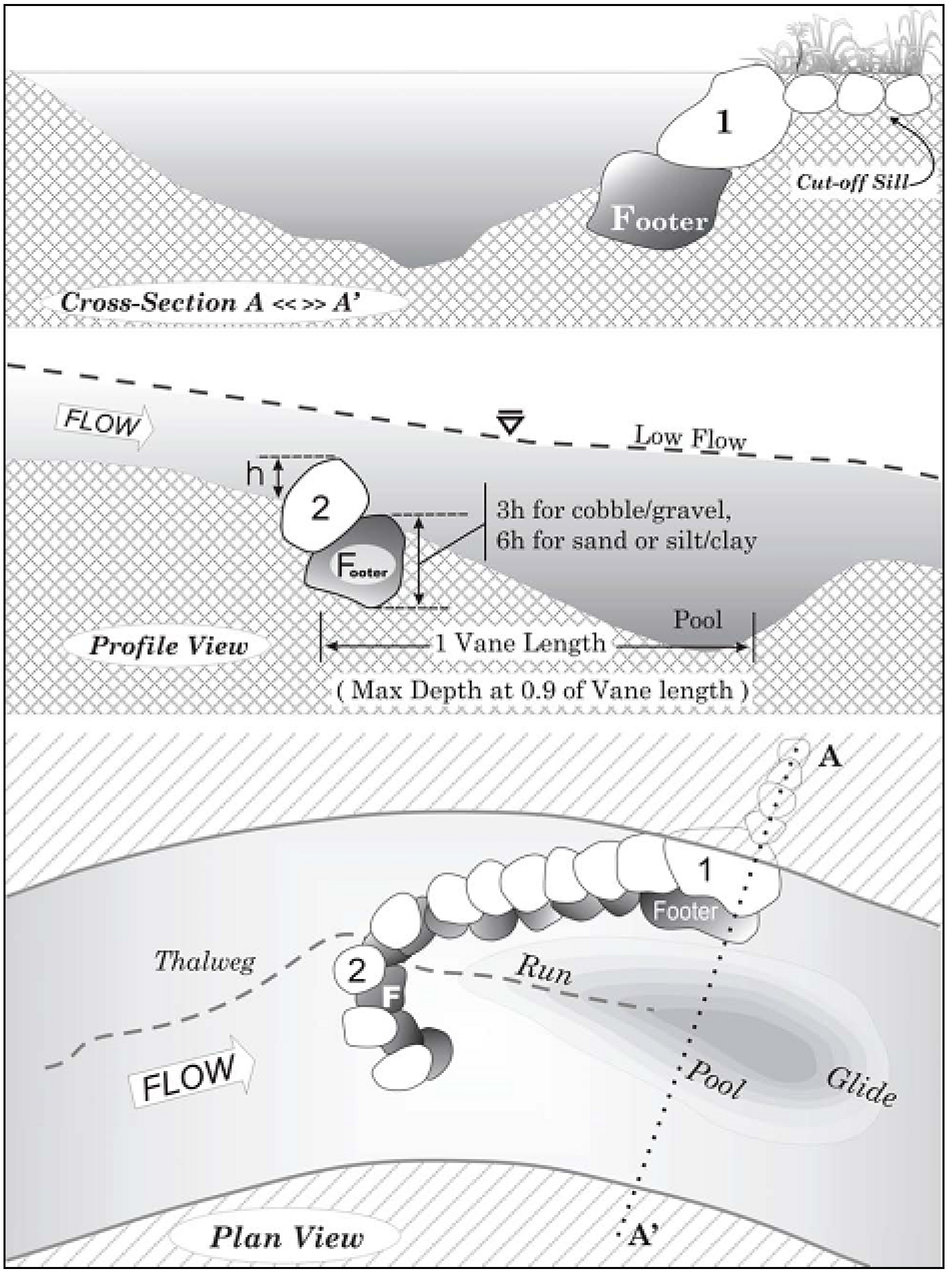

Figure 18. J-hook schematic from Rosgen (2006)

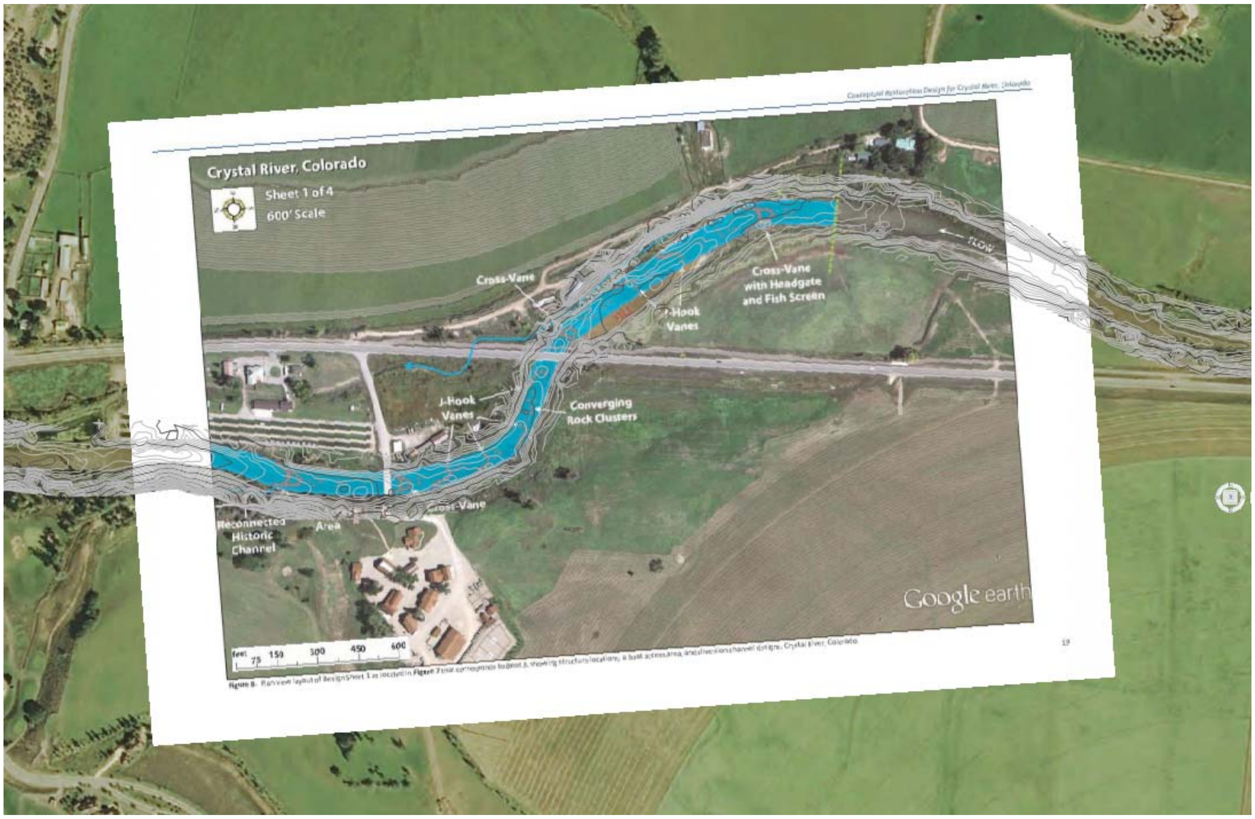

Figure 19. Beat 3 details overlaid with aerial and existing conditions surface, Wildland Hydrology (2014)

A-weirs and J-hooks within the simulated reach were designed following specifications of Rosgen (2006) as closely as possible. Crests at the throat of the structures were set at an elevation 0.8 ft above the upstream stream bed following recommendations from Reclamation (2015). Structure designs incorporated sloping arms meeting bankfull elevations extracted from the 1,650 ft^3/s existing conditions model. In some instances, the planimetric angles of the A-weir arms fell slightly outside of the recommended ranges. Modeled scour geometries deviated from recommendations from Rosgen (2006) and followed recommendations from observed scour topography. Scour patterns for A-weirs were dictated from laboratory observations of Scurlock et al. (2012) as illustrated in Figure 11. Equilibrium scour geometries for J-hooks were modeled after findings from Pagliara et al. (2013) as detailed in Figure 20. J-hook scour occurs due to acceleration around the structure tip and due to plunging of the flow over the crest, with locations of the maximum depths occurring proximal to the structure.

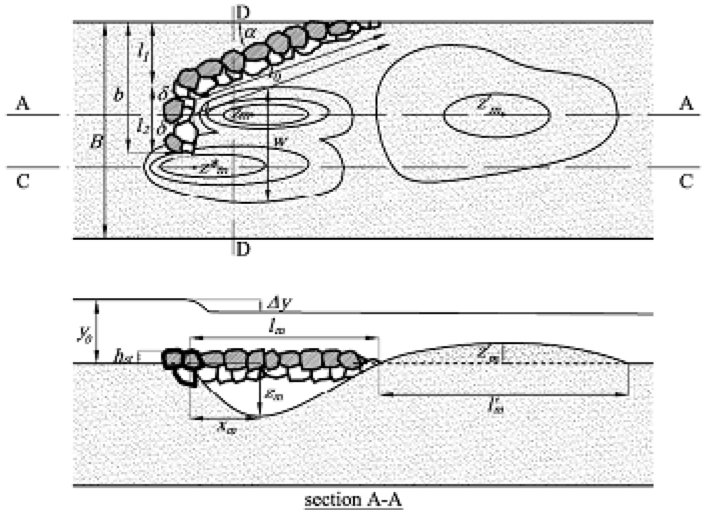

Figure 20. J-hook observed scour patterns, Pagliara et al. (2013)

Designed structures and equilibrium scour geometries were added to the existing conditions surface and a grid-independent mesh was generated. Mesh sizing was generally identical to the specific existing conditions grid used for bankfull elevation determination and comparable data, with a difference of the finer, 1.0 ft resolution in the vicinity of the structure crests. The models were simulated over the full range of the hydrograph at downstream boundary conditions as provided in Table 4. Numerical simulations were run until the solution achieved equilibrium hydraulic conditions.

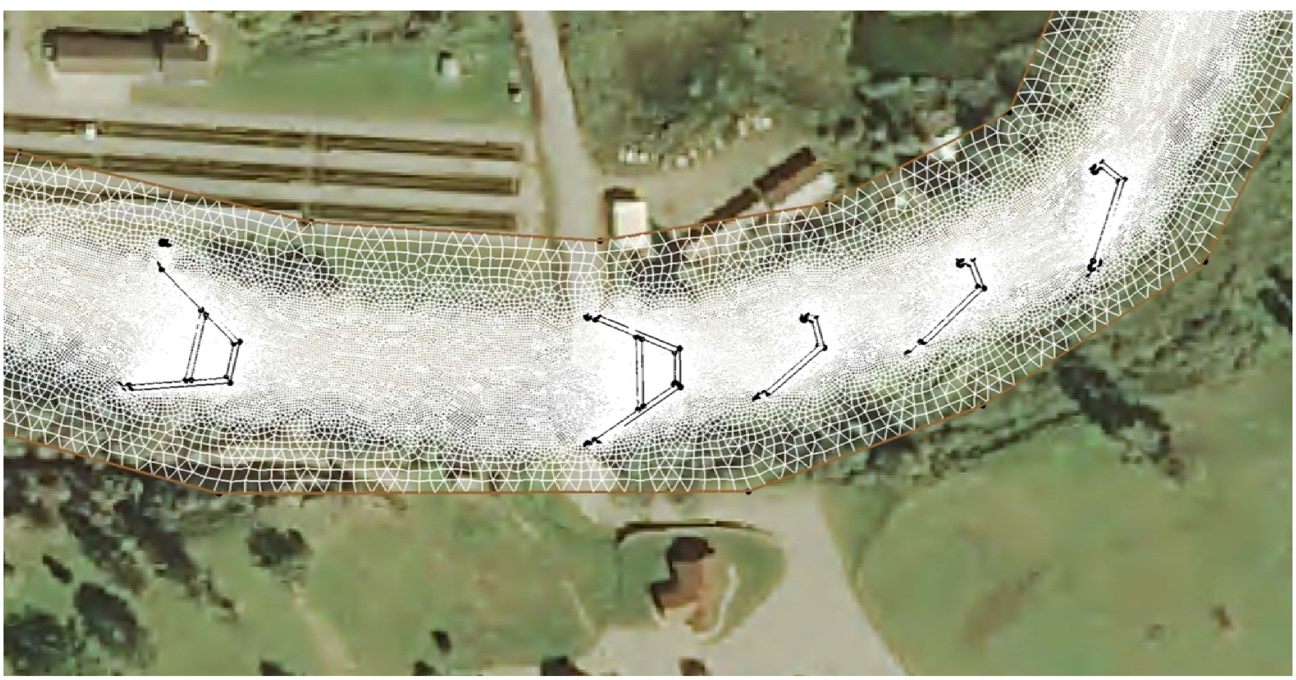

Figure 21. Planimetric view of conceptual restoration design computational mesh, near Mt Sopris Ranch Rd Bridge, flow direction to left

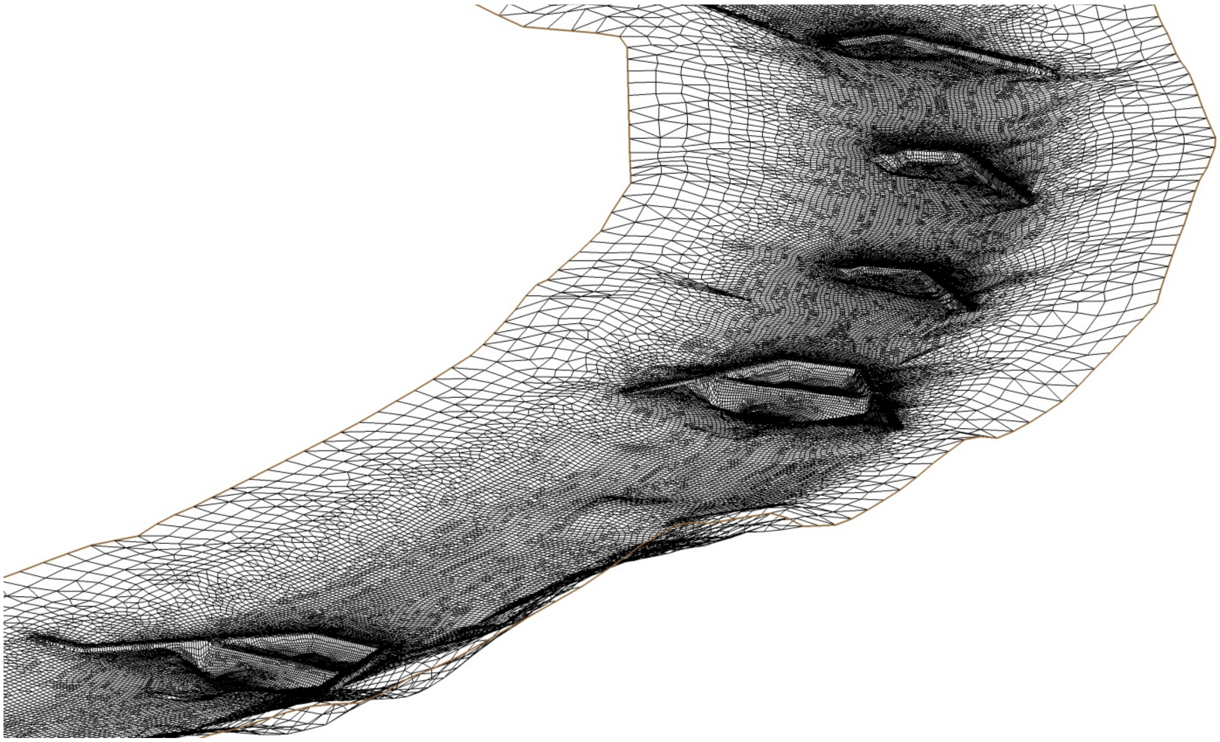

Figure 22. Perspective view of Wildland Hydrology (2014) conceptual restoration design computational mesh, near Mt Sopris Ranch Rd Bridge

Hydraulic effects from the application of the conceptual restoration structures included local backwater behind the structure crests, accelerated flow around the structure tips and over the structure crests, and a redistribution of hydraulics throughout the channel reach. Figure 23 illustrates the velocity magnitude distribution at existing conditions and after structure installation. Figure 24 details the difference to the existing conditions after structure installation. Hydraulic differences from the installation of structures were shown to have influence throughout the full channel reach, with velocity differences on the order of 1.0 ft/s in the vicinity of structure installations. Model results indicate that the conceptual structures may have significant effects on aquatic habitat.

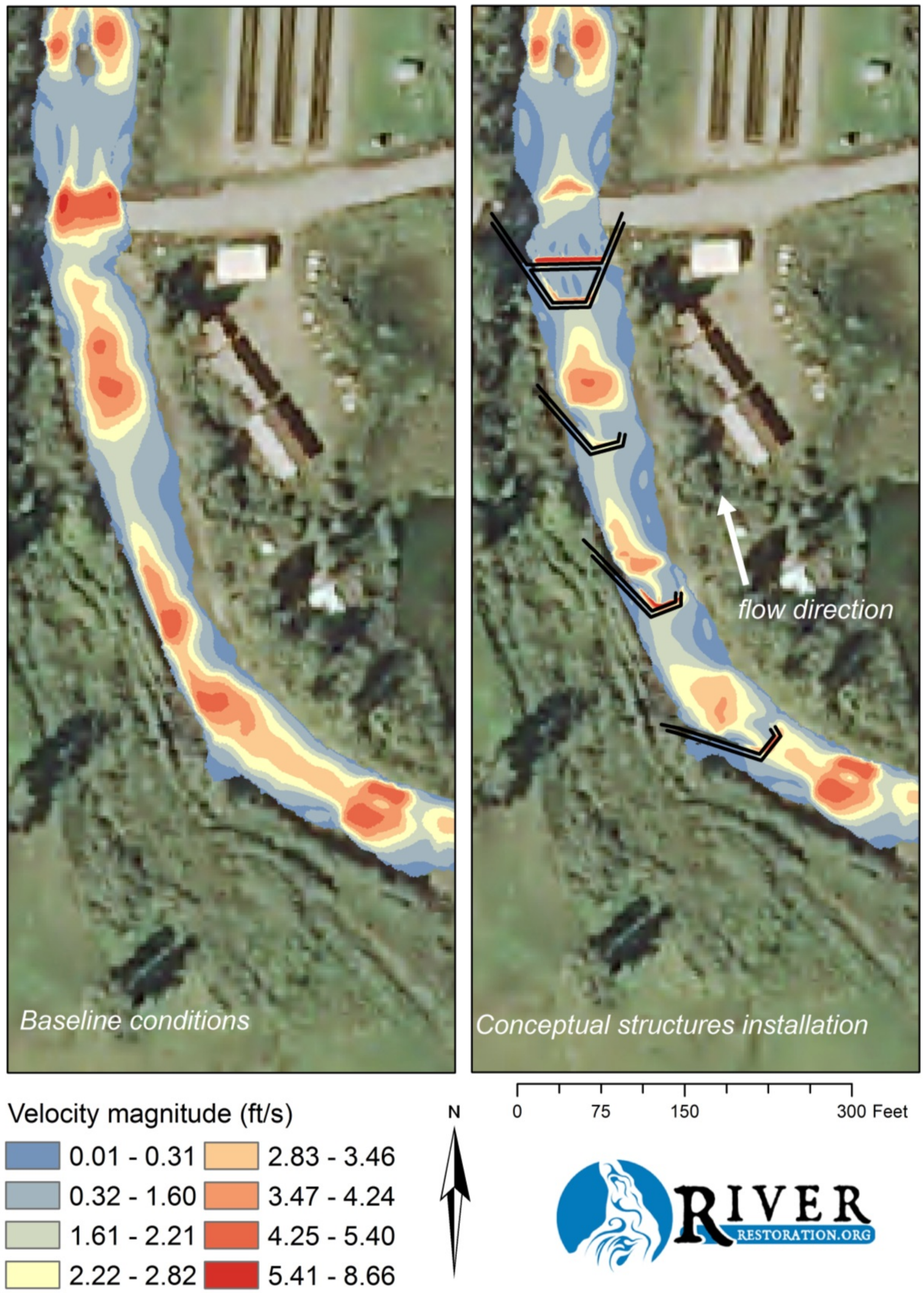

Figure 23. Velocities for existing conditions and Wildland Hydrology (2014) conceptual restoration, 100 cfs

Figure 24. Velocities difference from Wildland Hydrology (2014) conceptual restoration structures, 100 cfs

Modeling summary

One large scale existing conditions model and three localized structural alternatives were numerically evaluated to determine hydraulics pertaining to aquatic habitat. Models were developed using collected survey data and a thorough investigation to design guidelines and predicted scour topography. Data produced from modeling provides a comprehensive and robust analysis of the Crystal River under different restoration scenarios. The reach-long existing conditions model may serve as the best option for examination of hydraulic effects due to water management. Structural alternative models provide insight for hydraulic differences and regions of impact. Coupled with habitat suitability indices, the collective dataset provides a tool for assessment of various restoration scenarios on aquatic health in the Crystal River.

Discussion

The primary degradation of the Crystal River aquatic habitat and natural function is the depletion of flows. A depleted channel can be restored by supplementing instream flows or changing the structure of the channel to provide enhanced aquatic habitat. Three alternative structural configurations were evaluated through hydraulic modeling. Application of specific habitat indices to hydraulic data will be performed by Lotic.

Hydraulic modeling of the various restoration scenarios for the Crystal River elucidated the complexity of structural alternatives and requirement for thorough understanding of specific hydraulic response for various alternatives. Model results indicated sensitivity to the specifics of each design; optimizing habitat for a given alternative warrants comprehensive hydraulic design to maximize benefits. For example, the evaluated LFHC was designed based on hydraulic assumptions which may be optimized to better fit other aquatic species criteria or other objective. Thorough sediment transport analysis and structural design is required for any alternative incorporated to the river.

Final design of any structural alternatives requires a holistic view of the existing nature of the Crystal River and an approach coinciding with land owner objectives and instream flow management. Existing irrigation diversions hold flows and may function as fish barriers in their current form. Establishing fish ladders from irrigation ditches to the main thread of the Crystal River may provide habitat channels through otherwise impassible reaches of channel. Structural modifications for habitat enhancement may only be necessary to areas where connectivity through existing diversions is not feasible.

Proposed structural modifications are recommended for thorough evaluation to promote low-flow connectivity throughout the year as a primary habitat restoration objective. Modeling results indicated that regions of structural hydraulic influence do not propagate substantial distances in the channel. While structures may locally benefit habitat at low flows, there may exist a lack of connectivity between areas of improved habitat which prohibits passage and migration.

Summary

Ongoing investigations for river restoration of the Crystal River are considering water management scenarios and structural modifications. Current water management may create periods where flows are considered too low to maintain healthy aquatic habitat and instream recreational opportunity. Water management could increase base flows in the channel to facilitate specific flow depth and velocity goals. Structural modifications would aim to achieve the same goals at lower flow rates. To independently evaluate each restoration scenario, a series of hydraulic models were run to provide a comprehensive dataset for analysis. Data are suitable for continued hydraulic and habitat analysis and will serve as the basis for determining habitat impacts within the channel.

Four alternatives were numerically modeled with a depth-averaged, two-dimensional model of the Crystal River. Modeled alternatives included a reach-long existing conditions model and three structural modifications to representative full-reach subsets. Models were developed with field survey data coupled with structural design recommendations from associated literature. Flows evaluated ranged from extreme drought conditions to floods exceeding historical records. Data produced from the models are of the quality and resolution required to produce confident estimations of hydraulic trends and differences. Data exist for a total of 121 simulations. Data may be readily applied to habitat suitability models to gage the influence of evaluated alternatives on the aquatic health of the Crystal River. The reach-long existing conditions model serves to investigate relative changes due to water management scenarios across the full management reach. Structural models, with corresponding existing conditions models, provide relative changes to representative reaches of the Crystal River.

Modeling results indicated that structural alternatives may have substantial influence on river hydraulics. It is recommended that any structural alternative be thoroughly designed hydraulically to achieve management objectives while ensuring function and stability. Any structural modification would necessitate a long-term monitoring and adaptive maintenance plan.

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Source: "Crystal River." 39°17'06.58" N, 107°30'56.47" W. Google Earth. April 3, 2015. November 25, 2015.

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