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Design and Analysis of Ecosystem Features in Urban Flood Control Channels

Research and Development Office
Science and Technology Program
Final Report ST-2019-1726-01

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Bureau of Reclamation
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14. ABSTRACT *(Maximum 200 words):* Design features are developed and analyzed for urban flood control channels. The designs provide methods that can be implemented to improve aquatic habitat such as meandering, pools and riffles, flow deflectors, boulder clusters, and islands. A two-dimensional numerical model provides hydraulic data for the design features at a range of flows, while a physical model tests various configurations and densities of boulder clusters. The study demonstrates that the riverbed of urban channels can be redesigned to provide improved habitat and fish passage despite the constraints of an urbanized landscape.		
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Design and Analysis of Ecosystem Features in Urban Flood Control Channels

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Acronyms and Abbreviations

%	percent
2D	two-dimensional
3D	three-dimensional
ADV	acoustic doppler velocimeter
cfs	cubic feet per second
cm	centimeters
DEM	Digital Elevation Model
D_r	distortion ratio
ft	feet
ft^2	square feet
ft^3	cubic feet
ft/s	feet per second
G	Geometry
GeoTIFF	Geospatial Tag Image File Format
HEC-RAS	Hydrologic Engineering Center River Analysis System
H:V	horizontal:vertical
LA	Los Angeles
LFC	low-flow channel
LiDAR	Light Detection and Ranging
L_r	horizontal length scale
LSPIV	large-scale particle image velocimetry
m/s	meters per second
n	Manning's roughness
PIV	particle image velocimetry
U.S.	United States
WSE	water surface elevation
Z_r	vertical length scale

Executive Summary

Rivers and streams have been severely impacted by anthropogenic development and urbanization. Degraded ecological conditions have resulted from alterations to watershed hydrology and sediment yield, along with imposed constraints that limit natural channel adjustment and floodplain access. Urban streams have suffered from a decline in biological habitat values and species diversity as rivers have been channelized and confined. In some urban corridors, such as the Los Angeles (LA) River, streams have been completely channelized and lined with concrete to efficiently convey floods and minimize erosion. These original goals have largely been accomplished but have resulted in limited ecosystem services. Flow depths are uniform across the channel and velocities are increased with no refugia for aquatic species. Hydraulic conditions in confined urban rivers are often not suitable for native fish because of shallow depths and high velocities. Depth and velocity also serve as fish passage barriers in concrete lined channels thereby preventing fish from accessing their historical spawning grounds.

This research study examines how to redesign the channel bed to provide increased flow complexity and habitat heterogeneity within confined urban streams. The scope is limited to rehabilitation features that can be implemented within the current channel footprint because many urban systems do not have the space available to increase channel width and floodplain access. Water quality and other biological factors may limit the potential for native fish to permanently reoccupy urban streams throughout the year. Therefore, aquatic habitat improvement features are evaluated from a fish passage perspective. The goal of developing ecosystem features for confined urban rivers is to create suitable depth and velocity conditions for native fish. The LA River near downtown Los Angeles is selected as the pilot site for this study because of the extreme urbanization of the watershed and channel, and the interest and momentum that is being generated towards improving the ecosystem and aesthetic qualities of the river. Design features are scaled to the LA River pilot site for this report, but the concepts and analysis can be adapted to other urban channels.

A two-dimensional (2D) numerical model and a physical model are utilized to analyze existing conditions of the LA River and assess the efficacy of various ecosystem features. Design terrain surfaces are developed for 12 unique alternatives in addition to the existing channel. The underpinning concept of the design features is to increase the size and roughness of a low flow channel that would fit within the larger concrete flood control channel. Design features include a meandering low flow channel with pools and riffles, flow deflectors, a multi-threaded channel, backwater areas, boulder clusters, and mid-channel islands with alternating bank-attached bars. The design alternatives and the existing channel are evaluated at a range of flows using the 2D model. Hydraulics are assessed by applying a minimum depth fish passage criterion and then classifying velocity zones based on different resting and swimming speeds for Southern steelhead. The scaled physical model tests different configuration types and densities of boulder clusters to determine the potential of these boulder features to provide low velocity resting habitat for migrating fish.

Numerical model results confirm that the existing channel does not provide suitable depth and velocity conditions for fish passage at any flow. At low flows (less than about 200 cfs in the LA

River), a simple deepened and roughened low flow channel is enough to exceed the minimum depth requirement and provide velocities suitable for resting and migration. Discharges above base flow require additional channel complexity such as pools, flow deflectors, boulders, or islands. The design scenario with mid-channel islands and bank-attached alternating bars provides the greatest high quality (velocity less than 3 ft/s) and total resting area (velocity less than 5 ft/s) at mid-range discharges between 300 and 1,000 cfs. Boulder clusters, multi-threaded channels, and in-channel flow deflectors also provide significant benefits at these flows. At higher flows above 1,000 cfs up to 4,000 cfs (1% mean daily flow annual exceedance), the effectiveness of most design options declines because velocities increase above 5 ft/s. A design scenario with flow deflectors outside the low flow channel is one alternative to provide significant resting areas at these higher flows. Physical model test results indicate that boulder clusters are an effective technique to provide variability in the flow field including low velocity patches suitable for resting fish. There is no single optimum configuration, but the “V” cluster groupings of three rocks per cluster performed well when considering the number of boulders required for installation and the habitat benefits.

Recommended next steps include considering multiple depth criteria rather than a single threshold. A shallower depth is likely suitable for passage over short distances, while deeper water is needed for true resting or holding during migration. Design features can be further optimized by considering combinations of features, such as boulder clusters mixed with islands and bars, rather than the simpler design concepts developed during this study. Further research and sensitivity testing are recommended for the roughness values assumed in the numerical model. The 100-year flood stage is particularly sensitive to roughness, and the roughness at this flow is likely quite different than the roughness at low flows. Finally, additional physical model testing of boulder clusters is recommended such as lower density configurations, different locations, and different types of clusters. Data from the physical model should be used to develop, calibrate, and validate a 2D numerical model of the boulder clusters to determine if this is a viable tool for representing the flow field caused by these features.

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Introduction

Rivers and streams have been severely impacted by anthropogenic development and urbanization. Degraded ecological conditions have resulted from alterations to watershed hydrology and sediment yield, along with imposed constraints that limit natural channel adjustment and floodplain access. Urban streams have suffered from a decline in biological habitat values and species diversity as rivers have been channelized and confined. In some urban corridors, such as the Los Angeles (LA) River, streams have been completely channelized and lined with concrete to efficiently convey floods and minimize erosion (Figure 1). These original goals have largely been accomplished but have resulted in limited ecosystem services. Flow depths are uniform across the channel and velocities are increased with no refugia for aquatic species. Rivers that have been converted to urban flood control channels have also suffered from a disconnect between communities and their waterways, which has economic and social consequences. Revitalization can be accomplished by considering channel functions over a range of low to high flows, thereby transforming a single purpose (flood conveyance) waterway to a multi-purpose (flood control, habitat, aesthetics, and recreation) feature of the urban landscape. This research specifically examines how to redesign the channel bed to provide increased flow complexity and habitat heterogeneity within confined urban streams. Complementary actions would include watershed level planning efforts to increase stormwater capture, reduce flood peaks, and increase the space available to the river. However, these topics are not within the scope of the current study.

Figure 1. Los Angeles River looking downstream from 1st Street, annotated with approximate dimensions and base flow rate

This research to develop and evaluate conceptual alternatives addresses the question: How can ecosystem features be designed within urban flood control channels to increase habitat values without significantly raising flood stage? A two-mile reach of the LA River near downtown Los Angeles, from 1st Street to Washington Blvd, was selected as the pilot site. Figure 2 provides an overview map of the LA River watershed and Figure 3 shows an aerial image of downtown Los Angeles. The LA River provides an excellent pilot site for the study because of the extreme urbanization of the watershed and channel, and the interest and momentum that is being generated towards improving the ecosystem and aesthetic qualities of the river (e.g., City of Los Angeles, 2007; U.S. Army Corps of Engineers, 2015; lariver.org). Design features are scaled to the LA River pilot site for this report, but the concepts and analysis can be adapted to other urban channels.

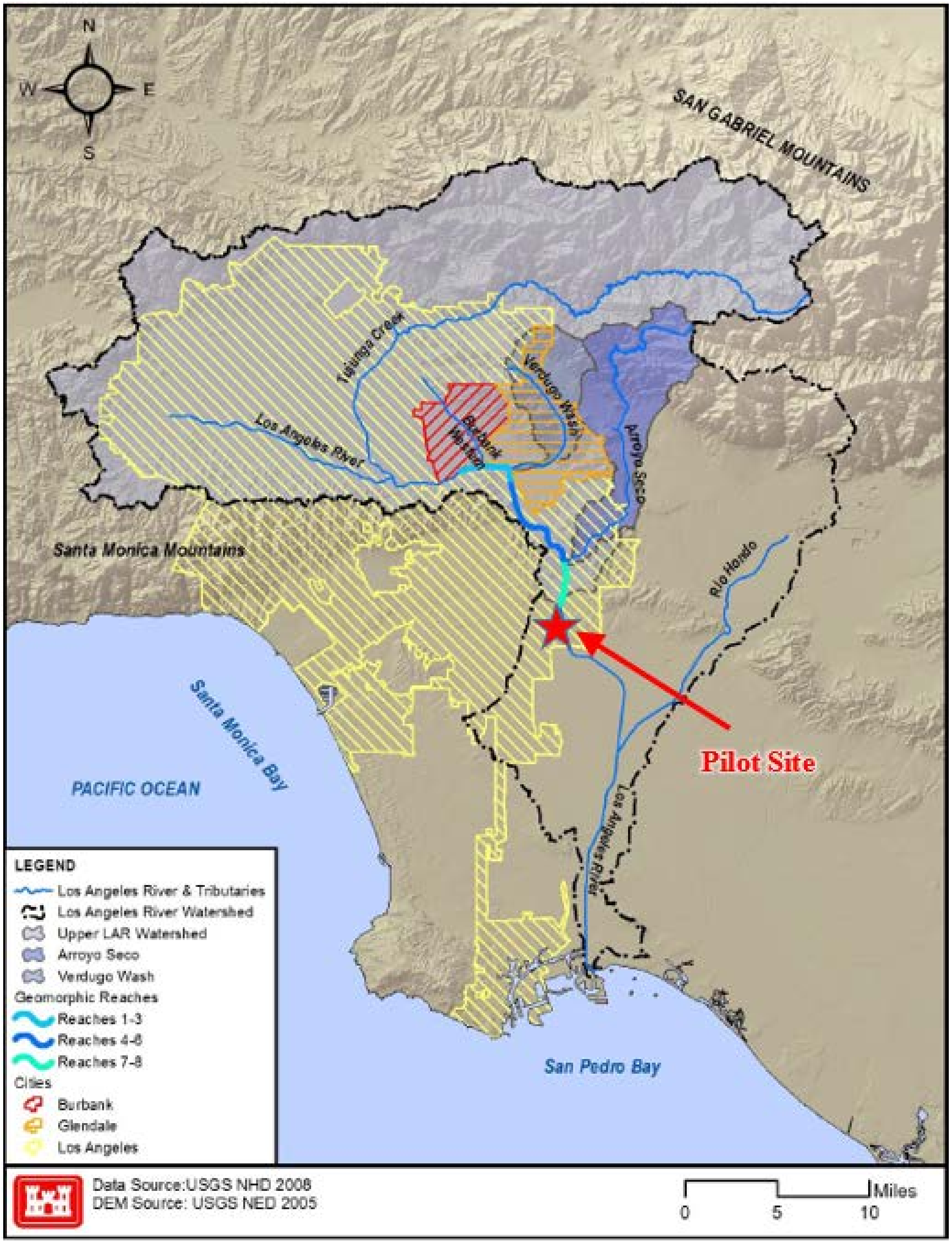

Figure 2. LA River watershed including locations of tributaries, geomorphic reaches of the U.S. Army Corps of Engineers restoration plan, and city boundaries (U.S. Army Corps of Engineers, 2015). Pilot site for this study is denoted with a red star.

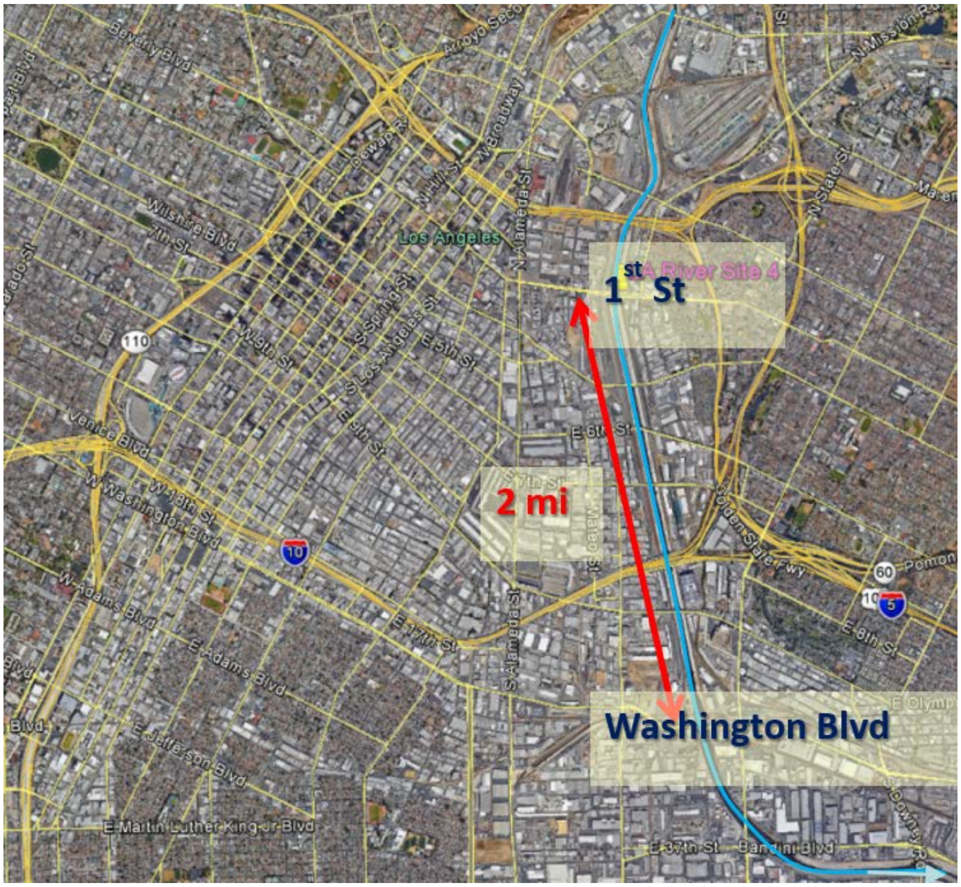

Figure 3. Aerial image from Google Earth of pilot site between 1st St and Washington Blvd near downtown Los Angeles. Blue line shows location and flow direction of LA River.

A series of large floods in the early 1900s, culminating with the 1938 flood, caused loss of life and extensive property damage. This led to construction of a concrete-lined channelized river beginning in 1938. The channel near downtown Los Angeles was designed to contain a discharge of 104,000 cfs, plus freeboard, which is similar to the 100-year flow of 109,000 cfs from later hydrologic analysis (U.S. Army Corps of Engineers, 2015). The design discharge is orders of magnitude larger than the current base flow (~100 cfs) throughout most of the year. About 80 percent of dry weather base flow is contributed from effluent discharge of three water reclamation plants (The Nature Conservancy, 2016). Recycled water has been identified as an important resource that can be used to improve urban streams by providing reliable flow augmentation (Bischel, et al., 2012). Although these effluent discharges have high treatment standards, there are water quality concerns because summer temperatures in the LA River may be too warm for native fish, which include steelhead, arroyo chub, and Santa Ana sucker (Mongolo, et al., 2017). However, warm summer temperatures should not preclude restoration efforts because the mainstem LA River historically served as an important migration corridor during winter months when temperatures are low.

Hydrology is a primary driver of river system function and is important to consider for analysis of existing channels and designs of future modifications. Flows in the LA River have been significantly altered since gage records began in 1930. Dry weather base flows have increased as various treatment plants have come online and discharged effluent into the LA River. Stormwater runoff peak flows have also increased as the watershed became increasingly urbanized, which decreased infiltration through an increase of impervious area. Figure 4 demonstrates the trend of increasing flow over time. The increased base flow around 1940 is attributed to channelization deepening the river during construction causing more groundwater to enter the channel (The Nature Conservancy, 2016). Subsequent flow increases in 1966, 1971, 1976, 1985, and 1991 correspond to either new water treatment plants or upgrades to existing plants.

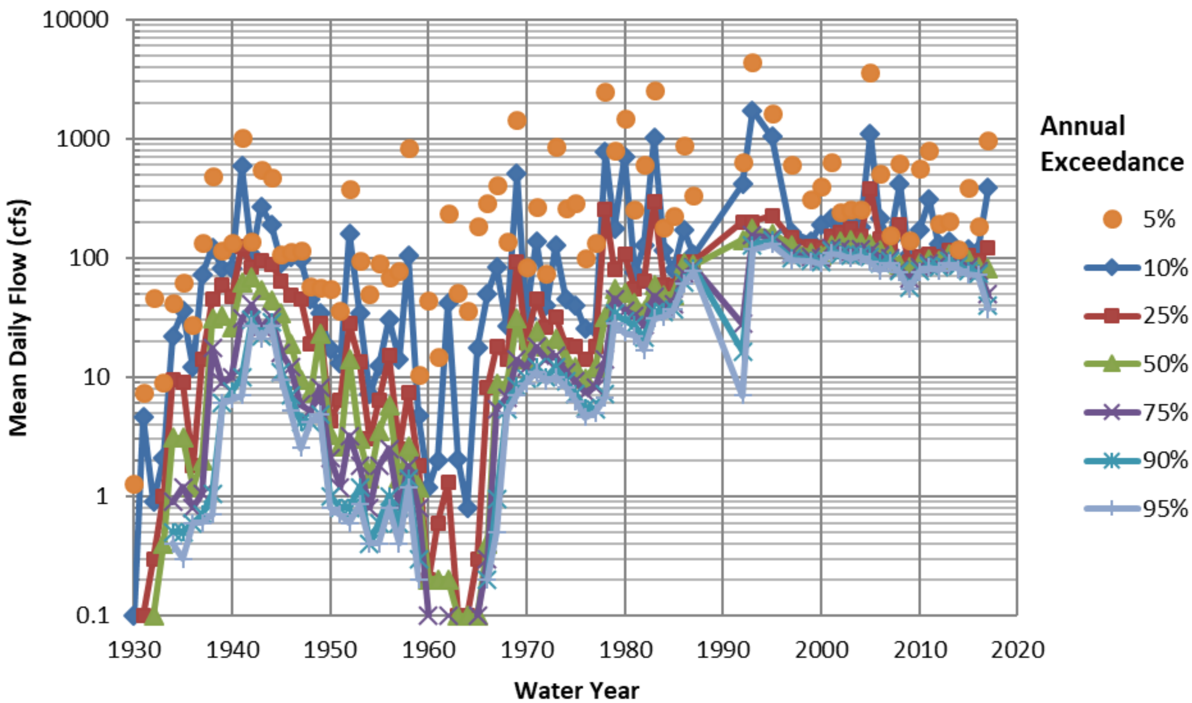

Figure 4. Various annual exceedance values for mean daily flow at the F57C Gage (LA River above Arroyo Seco) for Water Year 1930 to 2017

Figure 5 presents monthly exceedance flows since the Tillman Plant came online in Water Year 1985. The largest flows generally occur during the winter and the lowest flows occur during the summer. The median flow is remarkably consistent throughout the year at about 100 cfs. For this period of Water Year 1985 to 2017, flows are less than 150 cfs about 80 percent of the year, less than 300 cfs about 90 percent of the year, less than 1,000 cfs about 95 percent of the year, and less than 4,000 cfs about 99 percent of the year. These relatively low mean daily flow values are in stark contrast to instantaneous peak discharges determined by the U.S. Army Corps of Engineers (2015) that range from 22,900 cfs to 109,000 cfs for a 2-year and 100-year event, respectively.

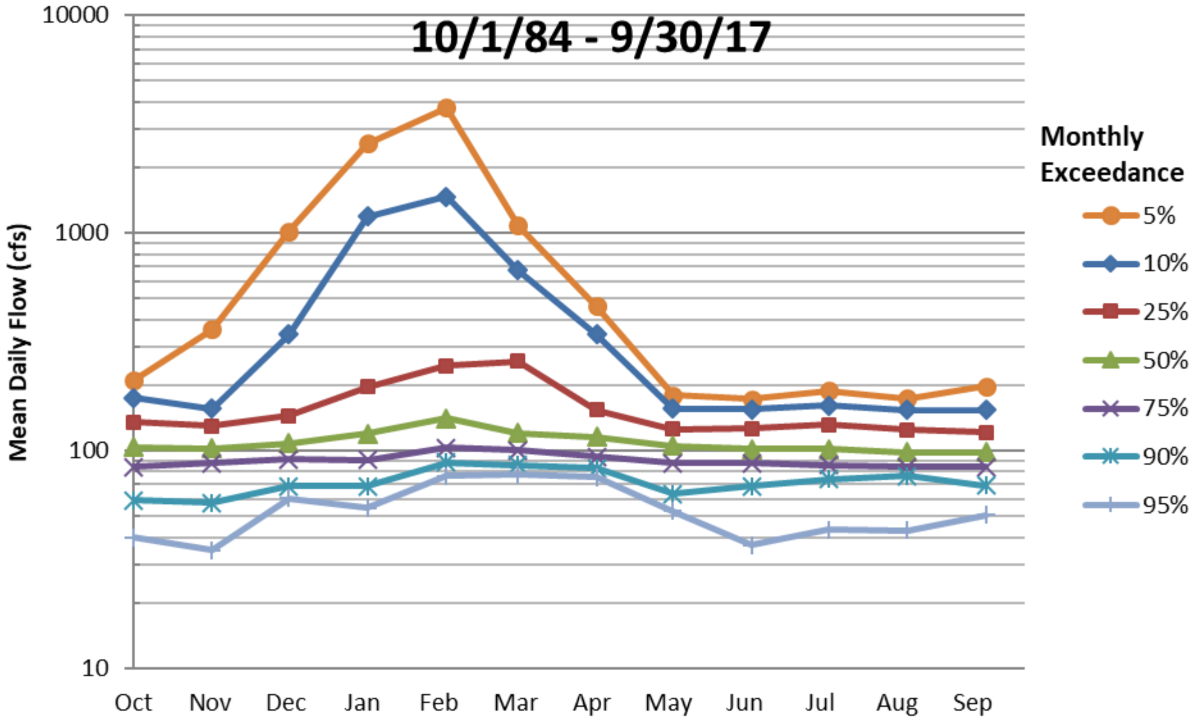

Figure 5. Various monthly exceedance values for mean daily flow at the F57C Gage (LA River above Arroyo Seco) for Water Year 1985 to 2017

The purpose of the 1938 design was to create a non-erodible channel that would quickly convey flood events from the watershed to the ocean. Therefore, it is not surprising that the low to medium flows that occur during more than 95 percent of the year provide no habitat for native aquatic species. These flows are either confined to a small notch or spread out at shallow depths across the concrete bed. Owing to the smooth concrete boundary and relatively steep channel slope (0.45%), flows in the LA River are generally supercritical. Even low flows have a velocity of 5 to 6 ft/s, which is above the cruising speed of steelhead trout (Caltrans, 2007). The shallow depth and high velocity of the LA River serve as a hydraulic fish passage barrier, regardless of the presence of other physical obstructions. Lack of fish passage prohibits access to the Arroyo Seco for example, whose headwaters provide favorable conditions for native fish. Therefore, the general objectives for LA River channel designs are to: reduce velocity, provide sufficient depth at low flows, provide refugia for native fish during migration, and not significantly increase flood stage. Increasing the channel and floodplain width would help meet these objectives but are not feasible to implement in some locations due to adjacent railways and extensive infrastructure, so the scope of the current study is confined to the existing channel footprint.

Design and Evaluation Criteria

The design and evaluation criteria consist of two primary elements: (1) aquatic habitat for native fish and (2) water surface elevation (WSE) at flood stage. The evaluation at flood stage is relatively straightforward: modeled WSE at the 100-year event for the various design concepts is compared to the existing channel WSE. Aquatic habitat was evaluated by selecting the Southern steelhead (*Oncorhynchus mykiss*) as the target species for habitat rehabilitation because of its swimming capabilities and lifecycle characteristics. Mongolo, et al. (2017) collected temperature data throughout the mainstem LA River and its tributaries. These data suggest that temperatures are likely too warm for native fish to survive in the LA River during the summer. Additionally, hydrology records indicate a low, inconsistent base flow prior to water treatment plants discharging effluent to the river. It is not a realistic biological goal to “restore” the LA River to pre-urbanized conditions. Rather, improving fish passage for the LA River as a migration corridor for steelhead is a more attainable target. This concept would apply to other urban streams as well. Regardless of seasonal migration patterns, longitudinal connectivity is an important feature of healthy rivers. Urbanized areas often bisect streams that have higher quality habitat upstream and downstream. Improving connectivity through urban corridors would increase the utility of stream segments that are less impacted.

Fish passage requires deep enough water for the fish to move freely and velocities that are less than the swimming speed. Barriers to fish passage are often localized obstructions such as a dam, culvert, or other structure. Geometry and roughness conditions of the LA River limit fish passage due to long reaches of shallow depth and high velocity even with no additional structural barriers. The goals of conceptual designs are to increase depth at low flows, reduce velocity during migration flows, and increase flow complexity by creating a more diverse arrary of velocities and depths to provide opportunities for fish to rest. Numerical criteria implemented to guide design development and evaluate design effectiveness are summarized below.

<u>Depth</u>: Taylor and Love (2004) recommend a minimum water depth of 0.8 ft for adult anadromous salmonids at stream crossings while Caltrans (2007) recommends a minimum depth of 1 ft. Habitat suitability curves provided by Allen (2015) are similar indicating that suitability increases with depth until reaching 1 ft. It should be noted that specific resting or holding habitat criteria likely requires a larger depth such as 1.5 ft, 2 ft, or greater, especially if instream or overhead cover is lacking (NRCS, 2007; AJ Keith, personnal communication). For the purposes of this study, it is assumed that depth is not a limiting factor if flow is deeper than 1 ft. Depth can be manipulated during the design process by changing the channel width and invert elevation. Design features developed during this study can be further adjusted to increase depth for improved holding areas, if desired. Table 1 lists the depth values applied for numerical analysis when evaluating fish passage for the various design options. Depth is used as a screening criteria, but the primary focus of this study is to assess the effect of rehabilitation techniques on the velocity suitability.

Table 1. Depth values used for fish passage analysis

Depth Range	Description
<1 ft	Depth would limit migration
>1 ft	Depth would not limit migration

Velocity: Several references such as Caltrans (2007) and Bell (1991) provide typical values for three different swimming modes for steelhead:

> Cruising speed: 0-5 ft/s. A speed that can be maintained indefinitely and is most commonly used for movement. Some references use "sustained" speed instead, but cruising is selected to avoid confusion with the next category.
>
> Prolonged speed: 5-12 ft/s. A speed that can be maintained for a few minutes up to 2 or 3 hours depending on the species. Some references use "sustained" speed instead.
>
> Darting speed: 12-26 ft/s. A speed that is employed for special circumstances but can only be maintained for a few seconds. Also known as "burst" speed.

Current conditions for many flows in the LA River are within the prolonged speed velocity category. If there is enough depth, steelhead can travel relatively significant distances at this speed, but eventually they will become exhausted and need to rest. The current uniform flow conditions do not provide any velocity areas less than 5 ft/s for resting to occur.

To account for areas that provide for recovery from prolonged swimming, the cruising speed was further divided into two classes assuming that it will be useful to distinguish velocities at the lower end of this range. Table 2 lists the velocity values applied for numerical analysis when evaluating fish passage for the various design options. Velocity results are only presented for areas that meet the mimimum depth threshold at a given flow because it is assumed that passage would not occur at shallower depths regardless of velocity. This simplification allows for a consistent comparison of fish passage across hundreds of combinations of design geometry and flow rate; it is recognized that passage is possible at local depths less than 1 ft and there may be improvements at depths greater than 1 ft. However, once the minimum depth is exceeded, the quality and ease of passage is primarily dependent on flow velocity.

Table 2. Velocity values used for fish passage analysis

Velocity Range	Description
0-3 ft/s	High quality resting velocity
3-5 ft/s	Low quality resting velocity
5-12 ft/s	Prolonged swimming speed
12-26 ft/s	Darting swimming speed

Conceptual Design Alternatives

A sequence of 13 terrain surfaces was developed and modeled, each representing a different low-flow geometry for the channel bed of the LA River. This includes the existing channel, known hereafter as Geometry 1, and 12 conceptual modifications (Geometry 2 through Geometry 13). Table 3 lists the key geometric and roughness parameters that were adjusted when developing the designs. Initial hydraulic analysis revealed that even low discharges tend to flow at supercritical, or near critical, depth. Therefore, increasing roughness within the low-flow channel (LFC) is required to increase depth and reduce velocity within suitable ranges for native fish. The increased roughness is needed regardless of other geometric changes made to the channel. It is assumed that the LFC roughness of the design concepts would be equivalent to that of a natural gravel or cobble bed stream with a Manning's n-value of 0.035. Further analysis is needed to determine the feasibility of a mobile cobble bed within the LA River LFC, which would likely require scour protection. An option to create a roughened channel with a fixed bed would be to grout roughness elements so they would not be transported by large flow events.

The basis of a redesigned LFC is to increase the width and depth to complement the increased channel roughness. A design discharge of 300 cfs was selected for the LFC capacity, which corresponds to the 10 percent annual exceedance for mean daily flows during 1985 to 2017. On average, there would be about 328 days per year where flow is contained by the redesigned LFC, and 37 days per year where flow spills out onto the adjacent concrete bed of the existing channel. It is expected that habitat conditions will improve as flow increases up to the LFC capacity and then decline as flow continues to increase above the LFC capacity. Therefore, the selection of 300 cfs as the design discharge attempts to balance habitat at base flows and habitat at larger discharges. The resulting dimensions selected for a uniform trapezoidal LFC within the pilot site are a top width of 64 ft and a depth of 2 ft. These dimensions are adjusted slightly for each of the conceptual alternatives but serve as a useful starting point for design. It is assumed that the top of bank for all LFC designs matches the elevation of the existing concrete at the bank location. Construction would require demolishing a portion of the existing concrete near the channel center and excavating a wider and deeper LFC.

Table 3. Low-flow channel design scenarios with description of key geometric features

Geometry #	Description	Planform	Width	Profile	Roughness
1	Existing	Straight	Constant	Constant	Concrete
2	Existing with roughened low-flow channel (LFC)	Straight	Constant	Constant	***Cobble LFC***, Concrete outside LFC
3	Increased width and depth LFC	Straight	***Constant (increased)***	***Constant (increased depth)***	Cobble LFC, Concrete outside LFC
4	Meandering LFC	***Meandering***	Constant (increased)	Constant (increased depth)	Cobble LFC, Concrete outside LFC
5	Variable width LFC	Straight	***Variable***	Constant (increased depth)	Cobble LFC, Concrete outside LFC
6	Pool-riffle LFC	Straight	Constant (increased)	***Variable (pool-riffle)***	Cobble LFC, Concrete outside LFC
7	Meandering, pool-riffle LFC	Meandering	Variable	Variable (pool-riffle)	Cobble LFC, Concrete outside LFC
8	Deflectors within LFC	Meandering	Variable	Variable (pool-riffle)	Cobble LFC, Concrete outside LFC, ***Boulder Deflectors***
9	Deflectors outside LFC	Meandering	Variable	Variable (pool-riffle)	Cobble LFC, Concrete outside LFC, ***Boulder Deflectors***
10	Multi-threaded LFC	***Multi-threaded***	Variable	Variable (pool-riffle)	Cobble LFC, Concrete outside LFC, ***Vegetated Islands***
11	Backwaters within LFC	Meandering ***with backwaters***	Variable	Variable (pool-riffle)	Cobble LFC, Concrete outside LFC
12	Boulder clusters within LFC	Straight ***with boulders***	Constant (increased)	Variable (pool-riffle)	Cobble LFC, Concrete outside LFC, ***Boulders***
13	Mid-channel islands and alternating bars within LFC	Straight ***with islands and bars***	Constant (increased)	Variable (pool-riffle)	Cobble LFC, Concrete outside LFC, ***Vegetated Islands and Bars***

A brief description of each geometry scenario is provided below. Figure 6 through Figure 9 show Digital Elevation Models (DEMs) for each configuration. The figures provide a representation of the geometry concept, which is then repeated throughout the pilot reach. It is recommended that final designs include more variability than what is shown here; the purpose of this analysis is to compare broad-scale types of LFC configurations.

Geometry 1 (existing channel): The existing conditions provide a useful basis to compare against the conceptual design alternatives. The DEM for existing conditions was developed by modifying LiDAR data using AutoCAD Civil 3D. LiDAR was obtained from a publicly available dataset made available by Los Angeles County and acquired as part of the Los Angeles Regional Imagery Acquisition Consortium (LARIAC). The data was collected in 2006 and consists of a 10 ft bare earth grid that was down-sampled from a 5 ft grid (LARIAC, 2006). LiDAR data did not penetrate the water surface so the LFC was added to the DEM using engineering drawings provided by the City of Los Angeles.

Geometry 2 (existing channel with roughened LFC): This alternative examines the effects of adding roughness to the LFC with no changes in geometry.

Geometry 3 (increased width and depth LFC): A uniform LFC is implemented to determine the effect of increasing the roughness and cross-sectional area of the LFC with no variability or additional features. The LFC has a top width of 64 ft and a depth of 2 ft. The bottom width is 30 ft and the banks have a side slope of 6:1 horizontal:vertical (H:V) for the lowest one foot near the bed and a side slope of 11:1 (H:V) for the upper one foot.

Geometry 4 (meandering LFC): This scenario maintains a constant top width and longitudinal slope while the meander belt width is equal to the full bottom width of the existing LA River. The alignment of the meandering channel follows a sine-generated curve and one meander wavelength is about 12 times the channel width. This provides a sinuosity of 1.03 for the design top width of 64 ft. At the apex of the meander bend, the outer bank has a steeper side slope than the inner bank.

Geometry 5 (variable width LFC): The side slopes and longitudinal slope are held constant as in Geometry 3, but the bottom width and top width are varied to create alternating wide and narrow sections. The narrow sections have a bottom width of 20 ft and a top width of 54 ft. The wide sections have a bottom width of 40 ft and a top width of 74 ft. The spacing between sections of equal width (i.e., between successive wide sections or successive narrow sections) was set to 6 times the channel top width, or half of a meander wavelength.

Geometry 6 (pool-riffle LFC): This scenario maintains a constant top width while varying the bed elevation to create a pool-riffle profile that follows a sine-generated curve. Bed elevation variability is 0.5 ft so that pool depths are 2.5 ft and riffle depths are 1.5 ft. The spacing between equivalent sections (i.e., between successive riffles or successive pools) was set to 6 times the channel top width, or half of a meander wavelength. Riffles are located to match the wide sections from Geometry 5 and pools are located to match the narrow sections from Geometry 5.

Geometry 7 (meandering, pool-riffle LFC): Elements from Geometries 4, 5, and 6 are combined to create this design. The meandering centerline is the same as Geometry 4 with pools located at the apex of meander bends and riffles located at the crossings midway between meander bends. Meander bends have a narrower bottom width and wider top width to account for the flatter slope of a point bar on the inside of each bend. Riffles have a constant side slope on the left and right banks, which creates a wider bottom width and narrower top width than the meander bends.

Geometry 8 (deflectors within LFC): Flow deflectors are added to the topography from Geometry 7 within the LFC. The flow deflectors are placed within the LFC along the inner bank just upstream of the meander bend. The purpose is to create flow separation where the current accelerates around the tip of the structure and causes an eddy or low velocity zone behind the structure near the bank. Placing the structure upstream of the bend along the inner bank enhances the function of the point bar by further reducing velocity in this area.

Geometry 9 (deflectors outside LFC): Flow deflectors are added to the topography from Geometry 7, but on the existing concrete rather than within the LFC. This allows the deflectors to be longer and create a larger effect at high flows compared to the in-channel deflectors from Geometry 8. As velocity increases within the LFC at higher flows (above ~1,000 cfs), the deflectors outside the LFC may provide important refugia for native fish.

Geometry 10 (multi-threaded LFC): This scenario modifies the topography from Geometry 7 by adding a secondary channel that simulates a chute cutoff across the inner point bar. The inlet to the secondary channel is at the riffle crest with an elevation 0.5 ft above the bed of the primary channel. A goal of this design is to increase wetted area of suitable depth and velocity while increasing shoreline length. This option was inspired by nearby streams such as the Ventura River that have a braided or multi-threaded planform. Similarly, the historical LA River also had a braided or multi-threaded planform before the river was channelized (The Nature Conservancy, 2016).

Geometry 11 (backwaters): This alternative also starts with the topography of Geometry 7 and then adds backwater features connected to the LFC. The goal of the backwaters is to create low velocity zones that are connected to the channel and may provide refugia for fish seeking to escape the main current. At higher flows when the banks of the LFC are overtopped, the backwaters serve as an outlet to direct these flows back to the LFC.

Geometry 12 (boulder clusters within LFC): Boulder clusters provide topographic diversity within the LFC that direct flows and provide eddies and low velocity zones through flow separation. Boulders and boulder clusters are examined in more detail using a scaled physical model, which is described later in this report. A topographic surface was created for one boulder cluster design at the full prototype scale for comparison to the other alternatives shown in this section. The boulder cluster topography is imprinted on the DEM from Geometry 6, which also provides the basis for the scaled physical model. Geometry 12 implements a V-cluster configuration where there are 3 clusters of 3 boulders each that are between the riffle crest and the downstream pool.

Geometry 13 (mid-channel islands and alternating bars within LFC): This scenario recognizes that in confined rivers a sequence of alternating bars and islands often form when there is not space for the channel to meander. A straight, pool-riffle channel was created with a top width of 100 ft and a shelf along each bankline that is 1 ft deep. Bars and islands are depositional features and were located to correspond to riffle locations. Bars and islands were sized to approximately match the cross-sectional LFC area from Geometry 6 and have 5:1 (H:V) side slopes and crest elevations that are 0.5 ft above where the LFC banks tie into the existing LA River.

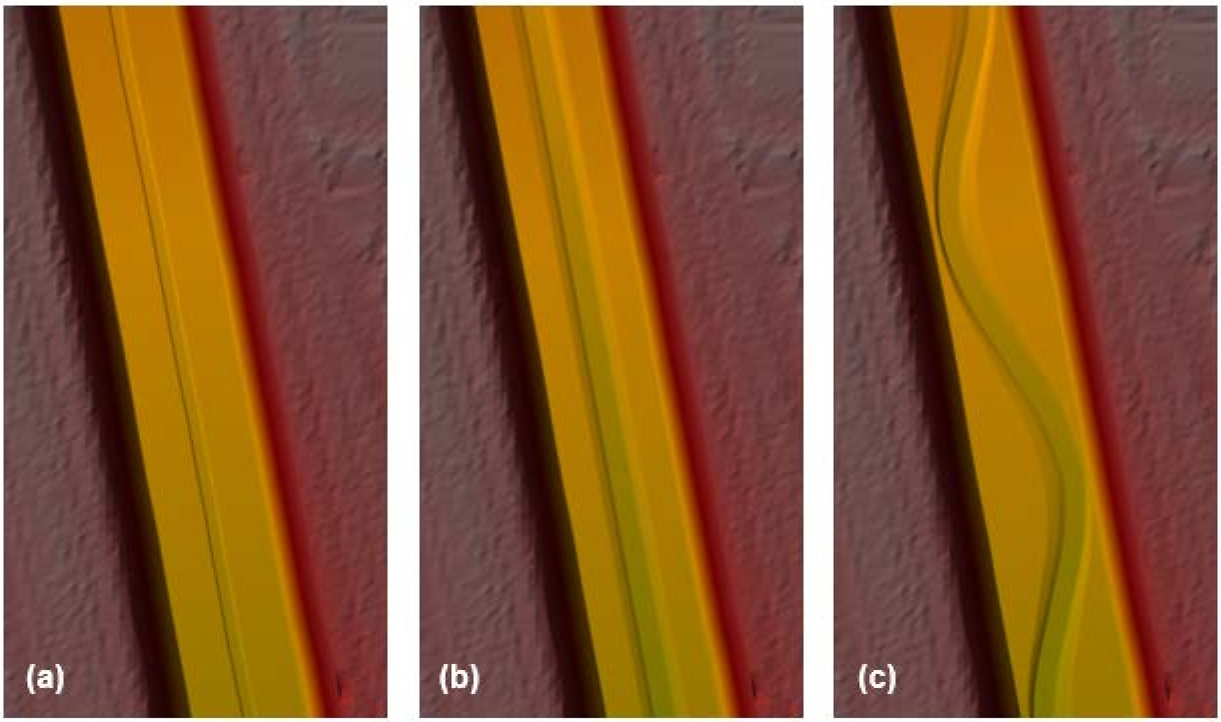

Figure 6. DEMs for (a) existing channel, (b), Geometry 3, and (c) Geometry 4

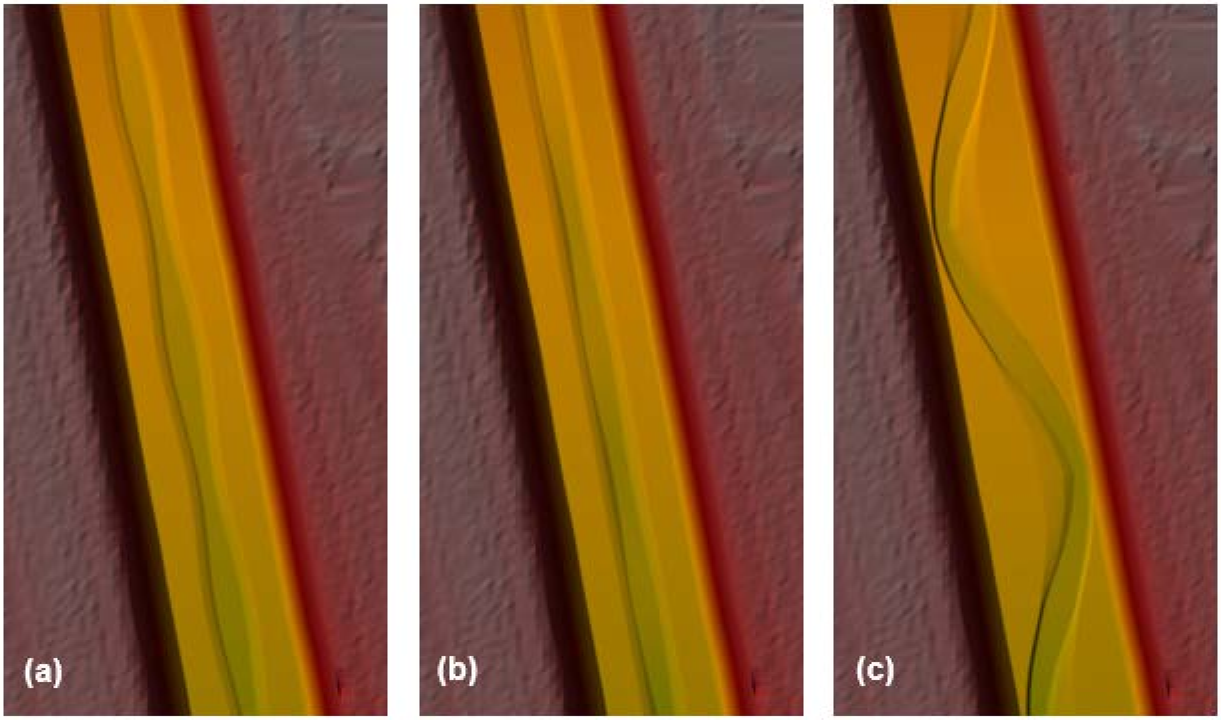

Figure 7. DEMs for (a) Geometry 5, (b), Geometry 6, and (c) Geometry 7

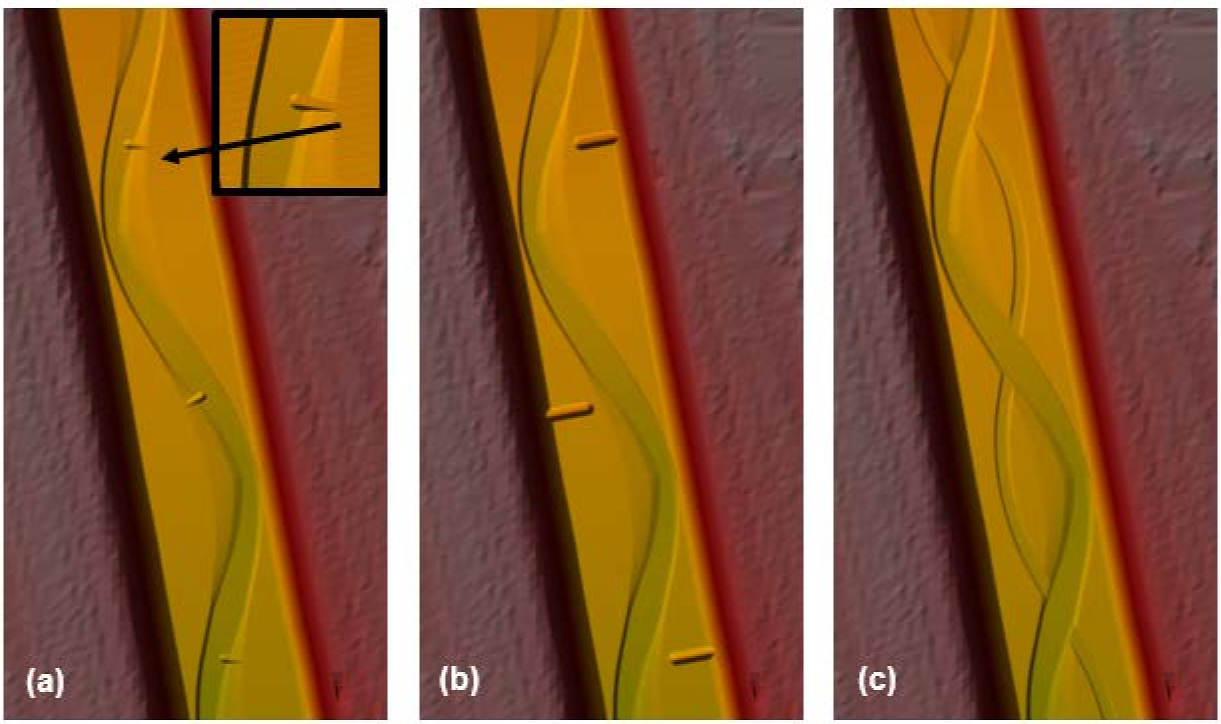

Figure 8. DEMs for (a) Geometry 8, (b), Geometry 9, and (c) Geometry 10

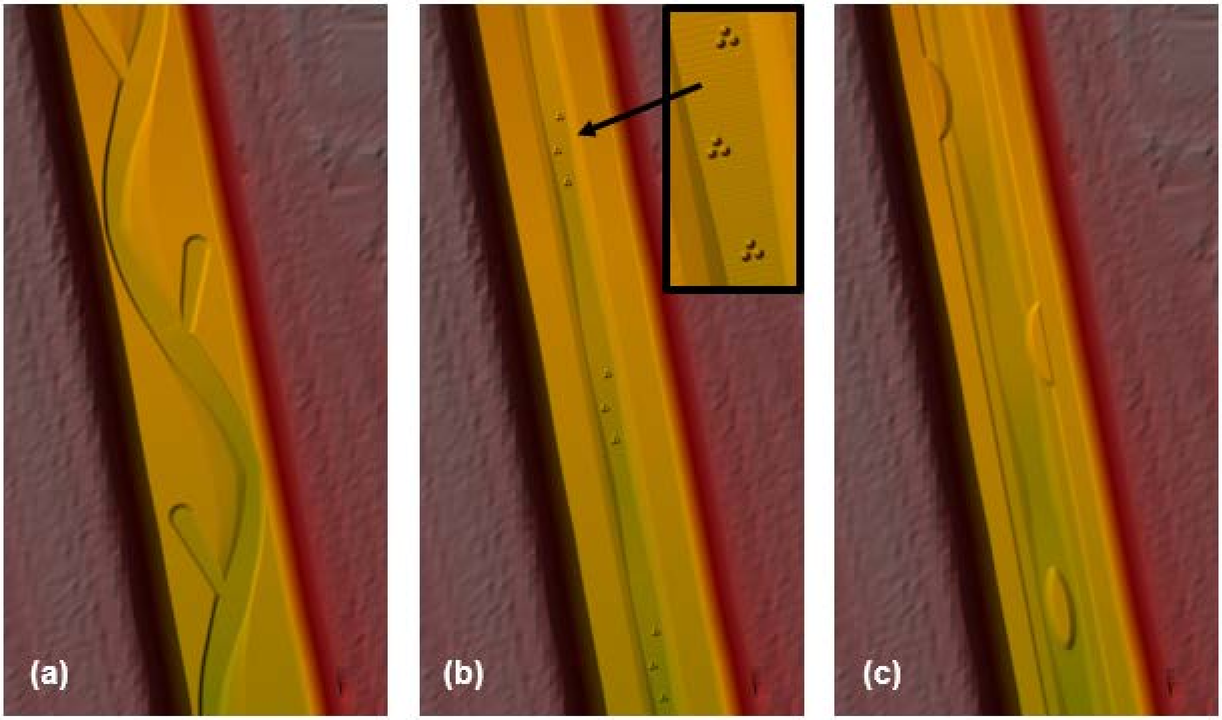

Figure 9. DEMs for (a) Geometry 11, (b), Geometry 12, and (c) Geometry 13

Numerical Modeling

Methods

The Hydrologic Engineering Center (HEC) River Analysis System (RAS) two-dimensional (2D) hydrodynamic model (Brunner, 2016), version 5.0.7, was used for this study. HEC-RAS 2D solves the unsteady flow equations using an Implicit Finite Volume algorithm. The program solves either the 2D Saint Venant Equations (with optional momentum terms for turbulence dispersion and Coriolis effects) or the 2D Diffusion Wave equations. For this study, the Momentum equation was used to better account for the complex hydraulics in the existing channel and the various concept designs such as the addition of flow deflectors and boulder clusters.

HEC-RAS 2D uses a subgrid model, meaning that the full resolution of the underlying terrain is used to calculate a single WSE for a given cell. An elevation-volume relationship is determined for each cell, and cells can be partially wet or dry. Water is exchanged between cells by cutting a detailed cross section at the cell faces. Therefore, it is important that cell faces be aligned with areas of high ground that serve as hydraulic controls. The following HEC-RAS 2D components were developed for this study:

- Terrain Layer (DEM)
- Computational mesh
    - Polygon boundary for 2D area
    - Selection of cell size (refinement regions)
- Spatially varied Manning’s roughness layer
- External boundary conditions
    - Upstream flow hydrograph
    - Downstream water surface calculated from normal depth
- Selection of computational time step
- Selection of simulation time

The development of 13 DEMs was previously described in the Conceptual Design Alternatives section. DEMs were imported to RAS Mapper using a gridded GeoTIFF (*.tif) format at 0.5 ft x 0.5 ft resolution. Table 4 lists the cell sizes and roughness zones used in the computational mesh for each geometry scenario. Manning’s n-values were primarily selected from Chow (1959) and were verified with additional data sources. A roughness of n = 0.013 was applied for the smooth concrete channel, n = 0.035 for the designed cobble LFC, and n = 0.05 for boulder elements and lightly vegetated islands and bars. The cell sizes were increased to a uniform grid of 10 ft for the 100-year simulations to satisfy Courant conditions due to the high velocity values. Topography of the design features is still represented by the subgrid model and energy loss and turbulence are accounted for through the increased roughness. The increased roughness for boulder clusters and flow deflectors at the habitat flows may be overestimated because the features are mostly accounted for in the finer mesh resolution. A limited roughness sensitivity analysis was performed for the 100-year flow simulations to assess the effect of different n-values on flood stage.

Table 5 shows the flows modeled for the fish passage and flood stage analysis. The fish passage flows range from a minimum potential low flow (10 cfs) to a fish passage high flow (4,000 cfs). The 100-year event of 109,000 was also modeled for comparison of water surface elevation at flood stage. Remaining model parameters include the computational time step and simulation time. The time step was set between 0.1 and 1.0 seconds to satisfy Courant conditions at the various flows and cell sizes. Simulation times ranged from 2 to 5 hours at each flow depending on how long it took for water surface elevations to stabilize and for all flow to be routed from the upstream boundary through the downstream boundary.

Table 4. Summary of computational mesh and roughness zones for fish passage 2D models

Geometry #	Description	Mesh Region	Cell Size	Roughness Region	n-value
1	Existing	LFC	4 ft	Concrete	0.013
		Background	8 ft		
2	Existing with roughened low-flow channel (LFC)	LFC	4 ft	Cobble LFC	0.035
		Background	8 ft	Concrete	0.013
3	Increased width and depth LFC	LFC	4 ft	Cobble LFC	0.035
		Background	8 ft	Concrete	0.013
4	Meandering LFC	LFC	4 ft	Cobble LFC	0.035
		Background	8 ft	Concrete	0.013
5	Variable width LFC	LFC	4 ft	Cobble LFC	0.035
		Background	8 ft	Concrete	0.013
6	Pool-riffle LFC	LFC	4 ft	Cobble LFC	0.035
		Background	8 ft	Concrete	0.013
7	Meandering, pool-riffle LFC	LFC	4 ft	Cobble LFC	0.035
		Background	8 ft	Concrete	0.013
8	Deflectors within LFC	Deflectors + Buffer	2 ft	Deflector Footprint	0.05
		LFC	4 ft	Cobble LFC	0.035
		Background	8 ft	Concrete	0.013

9	Deflectors outside LFC	Deflectors + Buffer	2 ft	Deflector Footprint	0.05
		LFC	4 ft	Cobble LFC	0.035
		Background	8 ft	Concrete	0.013
10	Multi-threaded LFC	LFC + Islands	4 ft	Islands	0.05
				Cobble LFC	0.035
		Background	8 ft	Concrete	0.013
11	Backwaters within LFC	LFC + Backwaters	4 ft	Cobble LFC	0.035
		Background	8 ft	Concrete	0.013
12	Boulder clusters within LFC	Boulders + Buffer	1 ft	Boulder Footprint	0.05
		2nd Buffer around Boulder Region	2 ft		
		LFC	4 ft	Cobble LFC	0.035
		Background	8 ft	Concrete	0.013
13	Mid-channel islands and alternating bars within LFC	LFC + Islands and bars	4 ft	Islands and Bars	0.05
				Cobble LFC	0.035
		Background	8 ft	Concrete	0.013

Table 5. Flows modeled in HEC-RAS 2D for analysis of fish passage and flood stage

Discharge (cfs)	Significance
10	Assumed minimum flow if additional water recycling from treatment plants is implemented
25	*Intermediate flow*
50	Low end of current base flow range (90-95% annual mean daily flow exceedance)
75	*Intermediate flow*
100	Median annual flow (50% annual mean daily flow exceedance)
125	*Intermediate flow*
150	High end of current base flow range (20% annual mean daily flow exceedance)
200	*Intermediate flow*
300	Nominal design capacity of LFC (10% annual mean daily flow exceedance)
500	*Intermediate flow*
1,000	5% annual mean daily flow exceedance
2,000	*Intermediate flow*
3,000	*Intermediate flow*
4,000	High flow passage design event (Q_{HFP}) (Lang & Love, 2014) (1% annual mean daily flow exceedance)
109,000	100-yr flow (U.S. Army Corps of Engineers, 2015)

Results

Fish Passage

Numerical modeling results are analyzed using the depth and velocity fish passage criteria listed previously in Table 1 and Table 2. Data analysis is from a subsection of the model domain between 1st Street and 7th Street, a distance of about 4,600 ft that includes six meander wavelengths or 12 pool-riffle sequences for geometry scenarios that have those features. The model domain extends about 2,000 ft upstream of 1st Street to Highway 101, and about 7,500 ft downstream of 7th Street to 26th Street. The analysis subsection was selected to avoid boundary condition effects and because of uncertainties in the LiDAR downstream of 7th Street.

Flows are less than 300 cfs about 90 percent of the year, so low flow data was first assessed to determine the performance of different geometry scenarios in meeting the minimum 1 ft depth requirement. Figure 10 shows two conditions for each geometry scenario: the minimum discharge where patches exceeding 1 ft depth start to occur and the minimum discharge where there is full connection from upstream to downstream at 1 ft depth. The existing channel (Geometry 1) does not have any 1 ft depth areas until a flow of 200 cfs and is not fully connected at 1 ft depth until a flow of 300 cfs. All geometry scenarios containing pools and riffles have patches of 1 ft depth at 50 cfs or less. However, there is not connectivity at 1 ft depth until 125 to 200 cfs. Geometry 13 (mid-channel islands and bank attached bars) likely requires a larger discharge for full connectivity because the low flow portion of the channel is wider at cross sections where islands and bars aren't present. The more uniform scenarios (Geometry 3 and 4) require a larger flow to have patches of 1 ft depth, but a lower flow to have continuous 1 ft depth. The uniformity of the low-flow channel provides a consistent 1 ft depth at a lower discharge than other alternatives. Designs can be further optimized if there is a target flow rate to achieve patches or connectivity at 1 ft, or other depths of interest. Using a minimum depth of 0.5 ft or 0.8 ft may also provide slightly different results.

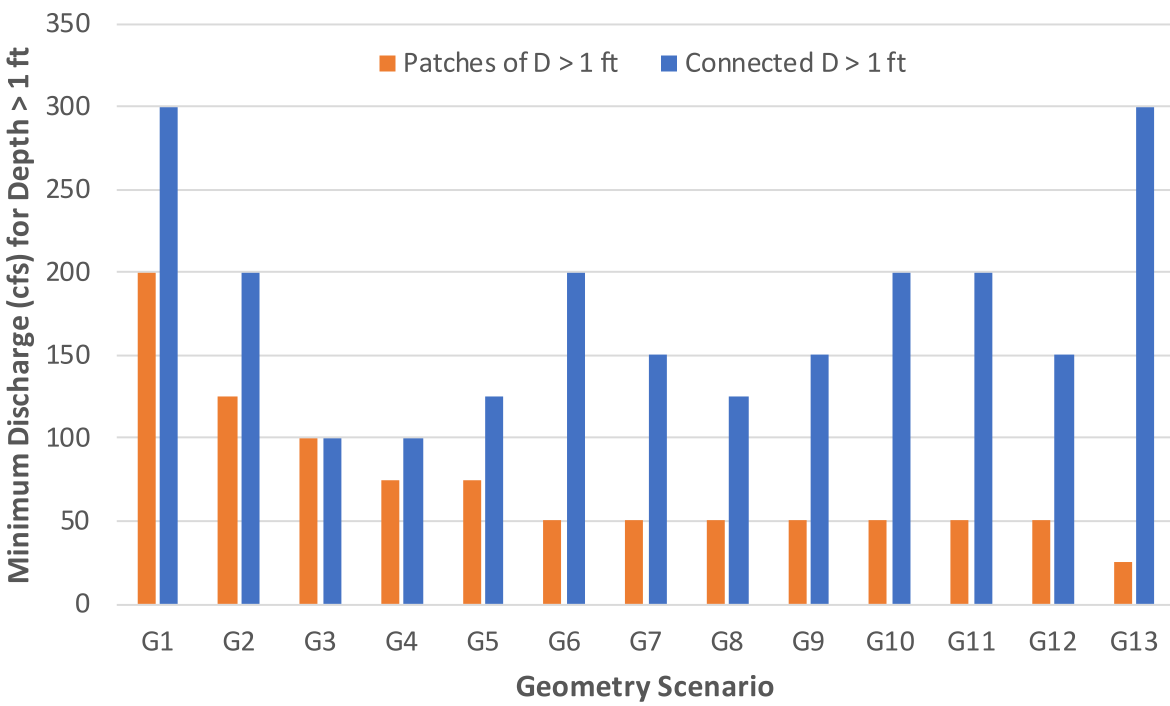

Figure 10. Minimum discharge required to achieve flow depth of at least 1 ft for each geometry scenario. Orange columns represent when patches of 1 ft depth areas first develop. Blue columns represent when there is full connectivity of 1 ft depth areas throughout the reach.

Velocity is categorized for all flows and locations that exceed a depth of 1 ft. Zones of less than 3 ft/s, 3-5 ft/s, 5-12 ft/s, and 12-26 ft/s are classified according to steelhead swimming modes (Table 2). Geometry scenarios are then compared within each velocity category across the range of fish passage flows from 10 cfs to 4,000 cfs (Table 5). The following graphs all use a consistent scale for resting area on the y-axis to facilitate a consistent visual comparison. The maximum value of 350,000 ft^2 is set based on the maximum total combined resting area (high and low quality) that is achieved for any scenario. For reference, the total inundated area of the analysis domain is about 780,000 ft^2 to 800,000 ft^2 at 4,000 cfs.

Figure 11 and Figure 12 present results for high quality resting area as a function of discharge for the various geometry scenarios. The existing channel (Geometry 1) does not have high quality resting areas at any discharge. High quality resting generally peaks at around 125 to 150 cfs for many design alternatives. As flow intensity increases it is difficult to maintain velocities less than 3 ft/s and the high quality resting area declines. Many design alternatives sustain some high quality resting areas up to about 1,000 cfs before declining to near zero at 2,000 to 4,000 cfs. Geometry 9 (deflectors outside the LFC) is an exception to this trend. The deflectors do not appreciably interact with the flow at discharges less than 1,000 cfs, but at 2,000 cfs or greater they create large eddies and backwater areas outside the low-flow channel.

Figure 13 and Figure 14 show similar results using total resting area, which includes both high quality and low quality (velocity less than 5 ft/s and depth greater than 1 ft). Resting area peaks at 500 to 1,000 cfs for most alternatives due to the less restrictive velocity threshold. Geometry 9 (deflectors outside the LFC) provides the largest total resting area at high flows, just as for the high quality resting area. Design scenarios that provide the greatest low-flow channel area and have multiple flow paths, namely Geometry 13 (mid-channel islands and bank attached bars) and Geometry 10 (multi-threaded LFC), have the largest total resting area at intermediate fish passage flows (300 to 1,000 cfs). At low flows less of 200 cfs or less there is not much variability between geometry scenarios, and it is more likely that depth will be the limiting factor rather than velocity.

Figure 15 synthesizes high quality resting, low quality resting, and prolonged swimming velocity categories for each geometry scenario across the range of modeled flows. The designs with pools and riffles are nearly identical at 50 cfs, but as Figure 10 showed, there are shallow areas less than 1 ft deep that are between the pools. The uniform designs (Geometry 3 and 4) provide the greatest resting area at 100 cfs with Geometry 4 (meandering LFC) being slightly larger because of the increased length. More variability between design options is evident as flow increases to 150 cfs. The effect of the in-channel flow deflector (Geometry 8) is noticeable as it creates additional resting area due to a backwater upstream of the structure and a low velocity eddy downstream of the structure. Geometry 13 (islands and bars) and Geometry 12 (boulder clusters) create the next largest high quality resting area due to similar hydraulic effects of backwater zones and flow separation around features. There is not much change between 150 and 200 cfs except for a redistribution between the high and low quality resting areas as velocities increase above 3 ft/s. At 500 cfs there is a significant increase in total resting area but a decrease in high quality resting. Total resting area declines between 500 and 1,000 cfs except for Geometry 12 (boulder clusters within LFC) and Geometry 13 (islands and bars). These elements obstruct portions of the flow to create localized areas of lower velocity. Flows above 1,000 cfs limit the effectiveness of most design features as resting area decreases and prolonged swimming area increases. Geometry 9 (deflectors outside the LFC) is the outlier by providing increased resting area because it is the only geometry scenario to implement features outside of the low-flow channel.

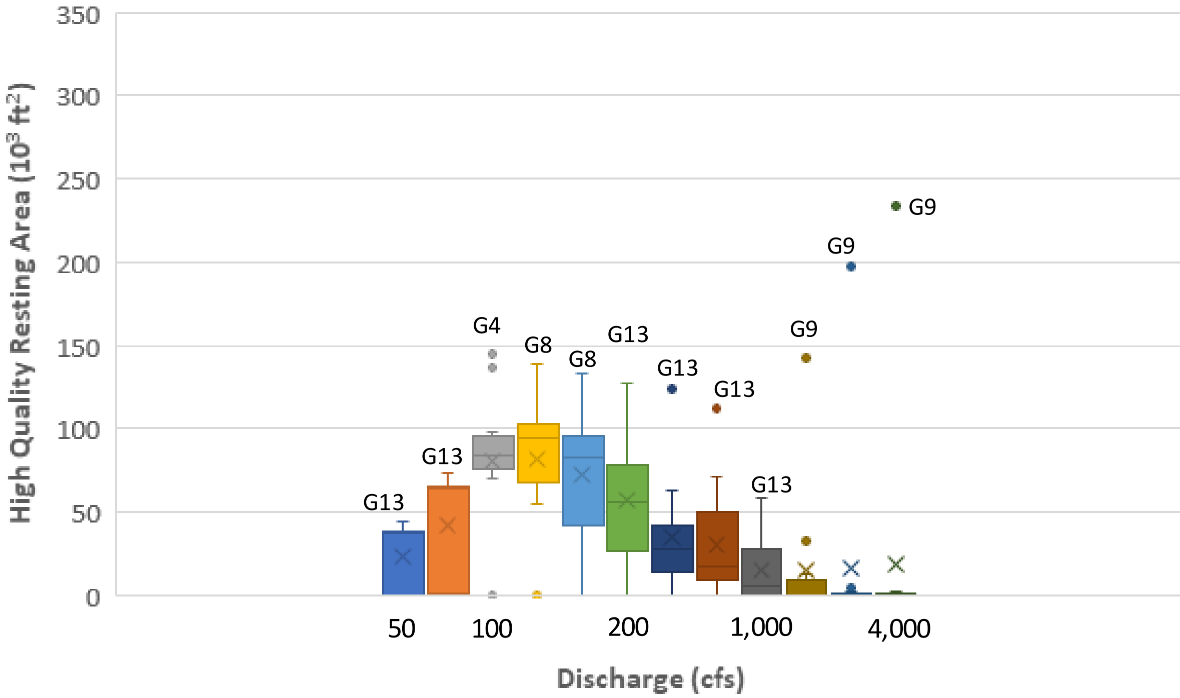

Figure 11. Box and whisker plot for high quality resting area (velocity < 3 ft/s and depth > 1 ft). Data range indicates variability between geometry scenarios at each discharge. Geometry scenario with largest area is labeled on plot.

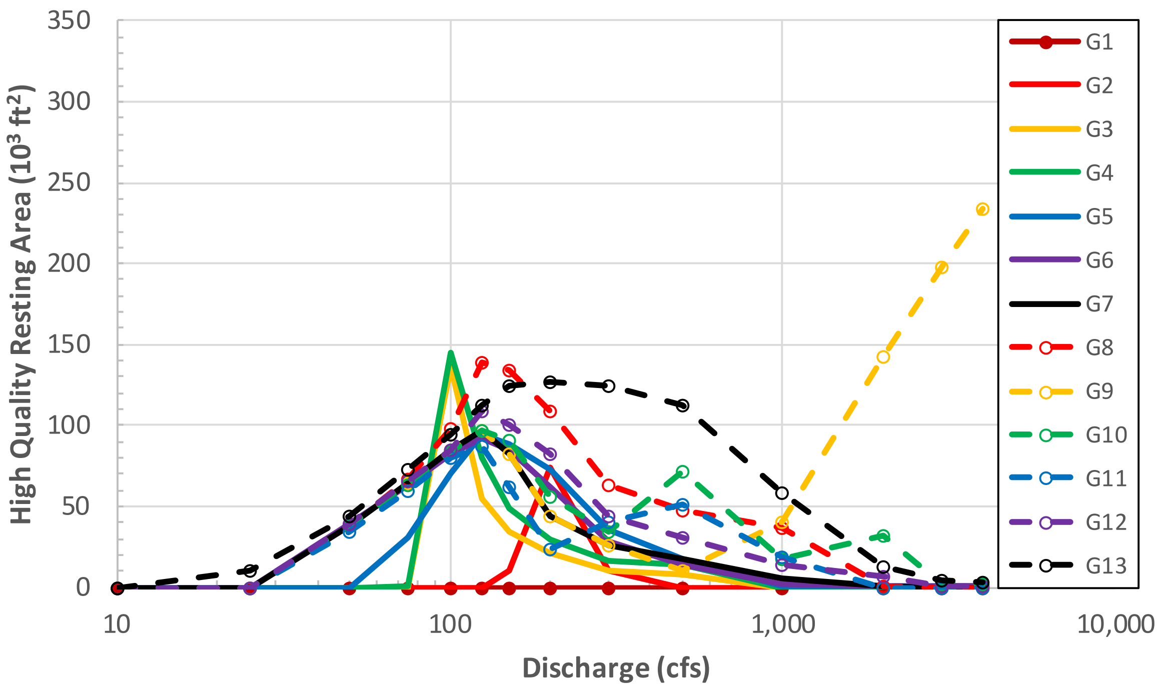

Figure 12. High quality resting area (velocity < 3 ft/s and depth > 1 ft) as a function of discharge for each geometry scenario

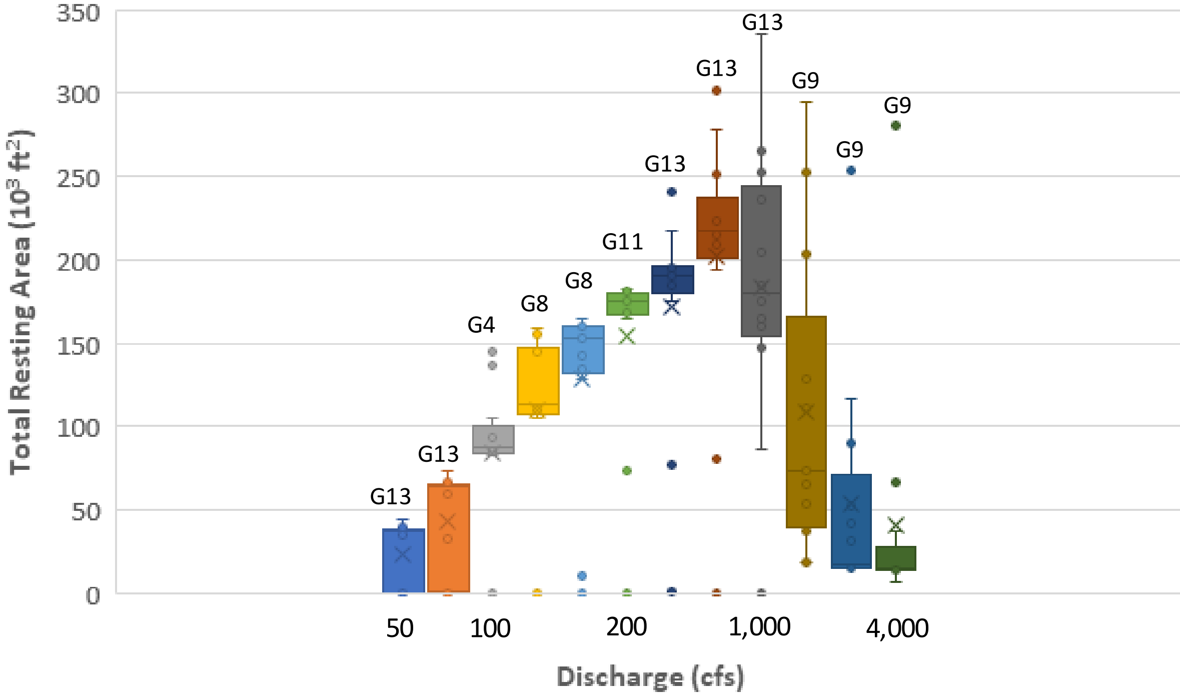

Figure 13. Box and whisker plot for total resting area (velocity < 5 ft/s and depth > 1 ft). Data range indicates variability between geometry scenarios at each discharge. Geometry scenario with largest area is labeled on plot.

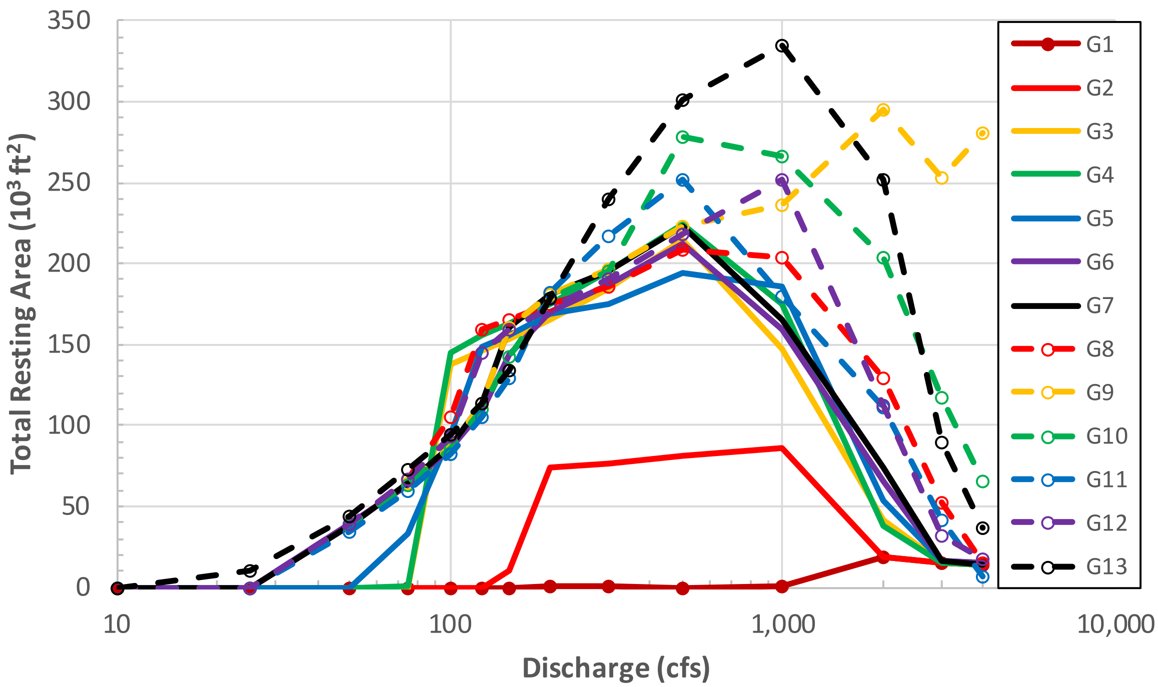

Figure 14. Total resting area (velocity < 5 ft/s and depth > 1 ft) as a function of discharge for each geometry scenario

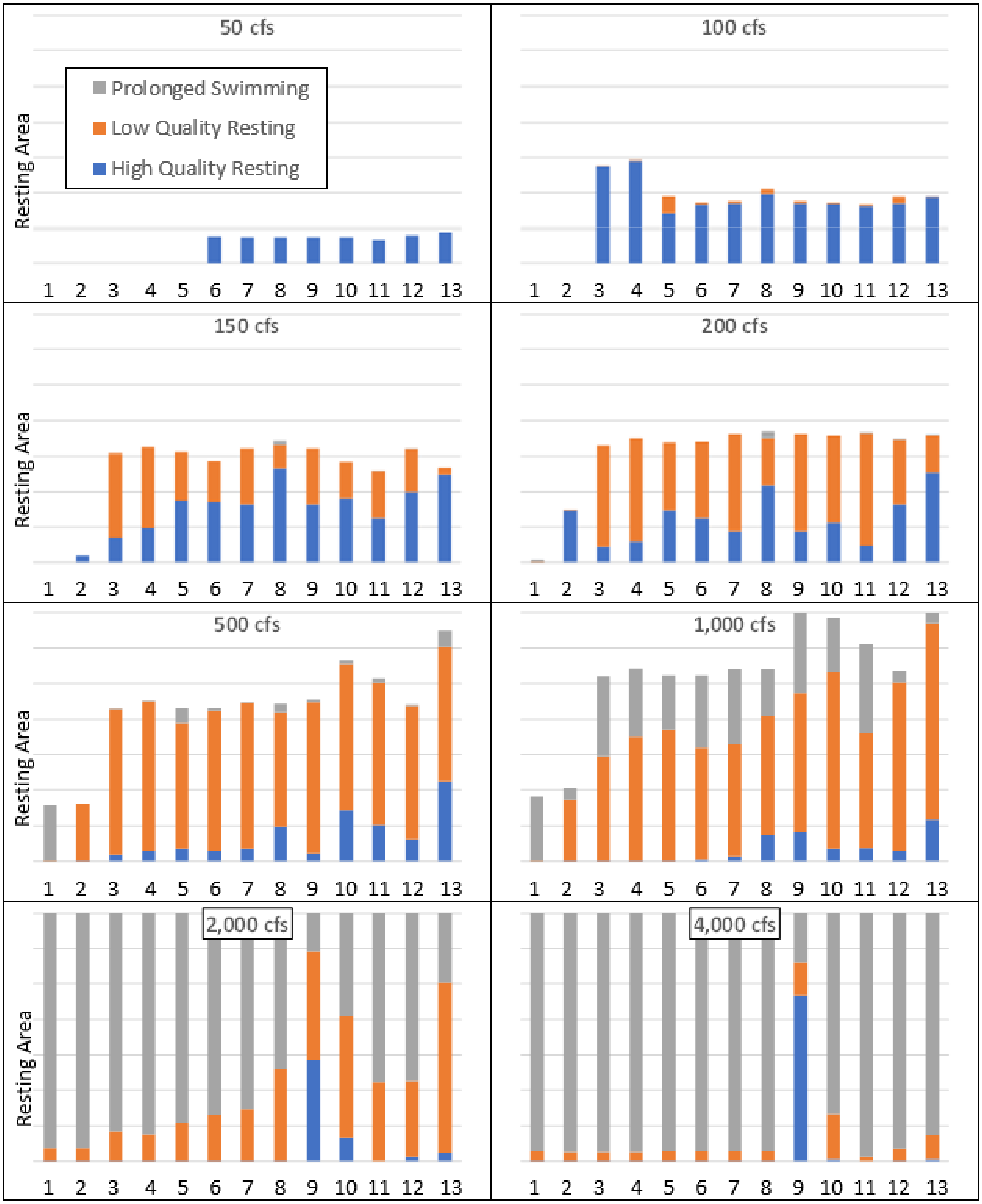

Figure 15. High quality resting (<3 ft/s), low quality resting (3-5 ft/s), and prolonged swimming (5-12 ft/s) velocity classification as a function of discharge for areas with depth greater than 1 ft. Numbers on x-axes denote geometry scenario. Resting area (y-axes) ranges from 0 to 350,000 ft^2 with gridlines representing increments of 50,000 ft^2.

Geometry scenarios 3 through 7 are all single thread channels with approximately the same dimensions. Variability is introduced by changing the width, planform layout, and bed profile, but the magnitude of variability is limited due to the constraints of the LA River and the relatively small scale of the low-flow channel. Therefore, it is not surprising that results are similar between these design options. However, geometry scenarios 8 through 13 warrant additional discussion because of their unique design features. These designs generally use Geometry 7 (meandering pool-riffle LFC) as the starting point and add a component. Graphs presented below compare results for each of these design features to results from Geometry 7 to illustrate any differences.

Geometry 8 (deflectors within LFC): High quality resting area is consistently increased between 100 and 1,000 cfs (Figure 16). Total resting is increased between 1,000 and 3,000 cfs. Figure 17 shows the velocity field created by the structure where there is flow acceleration around the tip and reduced velocity along the bank upstream and downstream due to expansion and contraction. There is additional near zero velocity area near the bank downstream of the structure, but it is less than 1 ft deep at 500 cfs and not shown on the figure.

Geometry 9 (deflectors outside LFC): There is no change from Geometry 7 at flows less than 1,000 cfs because the LFC design is the same (Figure 18). The structure has similar effects at high flows as the in-channel deflectors (Geometry 8) have at low flows. The structure blocks a larger flow area so the resting velocity zone is significantly greater (Figure 19)

Geometry 10 (multi-threaded LFC): There is minimal change at flows less than 500 cfs because depth in the secondary channel is less than 1 ft (Figure 20). High quality and total resting areas increase at 500 cfs when there is sufficient depth in the secondary channel, which provides refuge from higher velocities in the main channel (Figure 21).

Geometry 11 (backwaters): High quality and total resting area is slightly decreased at flows less than 300 cfs because the increased areas of the backwaters reduce the average depth in the channel (Figure 22). There is an increase in resting area at 300 cfs, and especially at 500 cfs, when the backwaters are sufficiently inundated to realize the benefit of these lower velocity zones (Figure 23).

Geometry 12 (boulder clusters within LFC): Boulder clusters provide small but consistent increases in high quality resting at nearly all flows above 100 cfs (Figure 24). There is a significant increase in total resting area at 1,000 cfs. Figure 25 illustrates the benefits of the boulders providing sheltered wake zones immediately downstream, but the overall resting area is limited by the size and density of the boulders.

Geometry 13 (mid-channel islands and alternating bars within LFC): This alternative generally provides the largest increase to high quality and total resting at flows between 200 and 1,000 cfs (Figure 26). The increased channel width and the larger scale of the island and bar features result in larger habitat areas at these intermediate flows (Figure 27). Bars and islands provide similar hydraulic functions as flow deflectors and boulder clusters by causing backwater effects and flow separation through expansions and contractions of the low-flow channel.

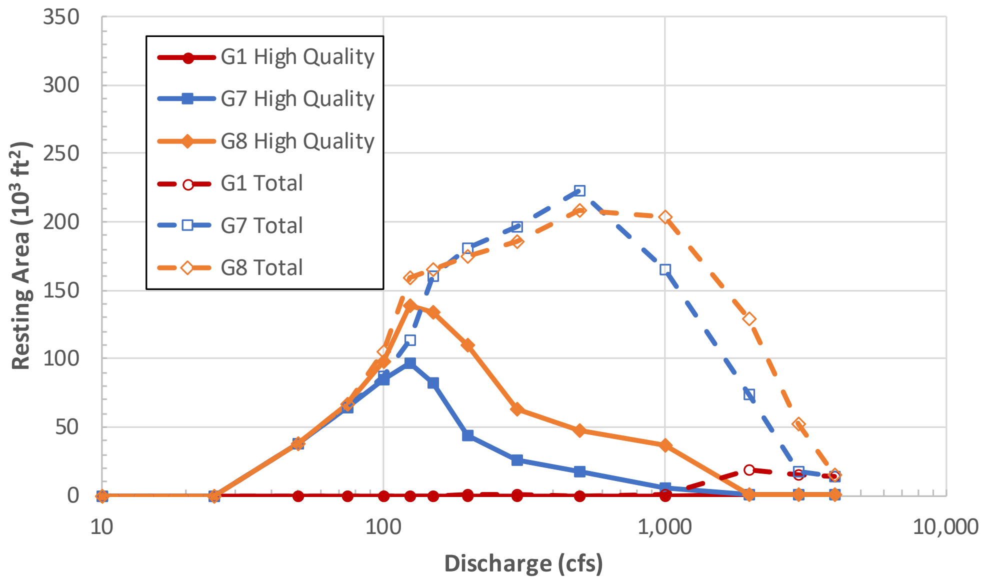

Figure 16. Comparison of high quality (velocity < 3 ft/s and depth > 1 ft) and total (velocity < 5 ft/s and depth > 1 ft) resting area for Geometry 7 (meandering pool-riffle LFC) and Geometry 8 (deflectors within LFC)

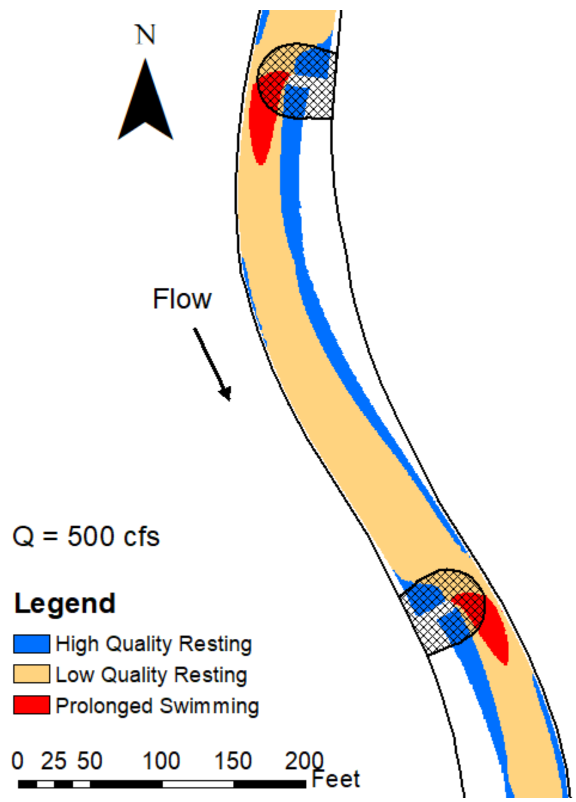

Figure 17. Velocity classification at 500 cfs for Geometry 8 (deflectors within LFC). Depths less than 1 ft are not shown. Black outline represents meandering LFC top of bank. Black hatching represents mesh refinement zone, including a buffer, for representation in 2D model.

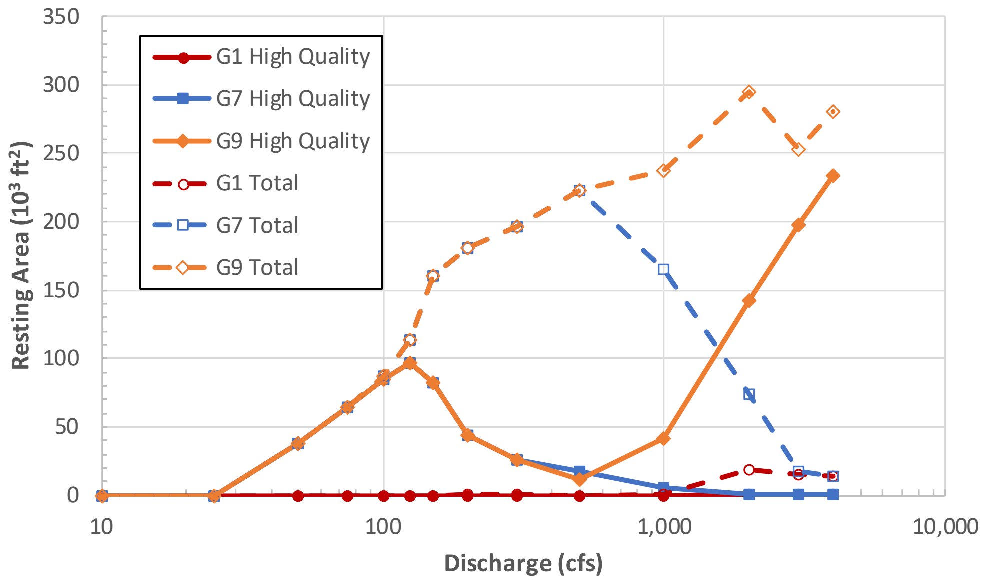

Figure 18. Comparison of high quality (velocity < 3 ft/s and depth > 1 ft) and total (velocity < 5 ft/s and depth > 1 ft) resting area for Geometry 7 (meandering pool-riffle LFC) and Geometry 9 (deflectors outside LFC)

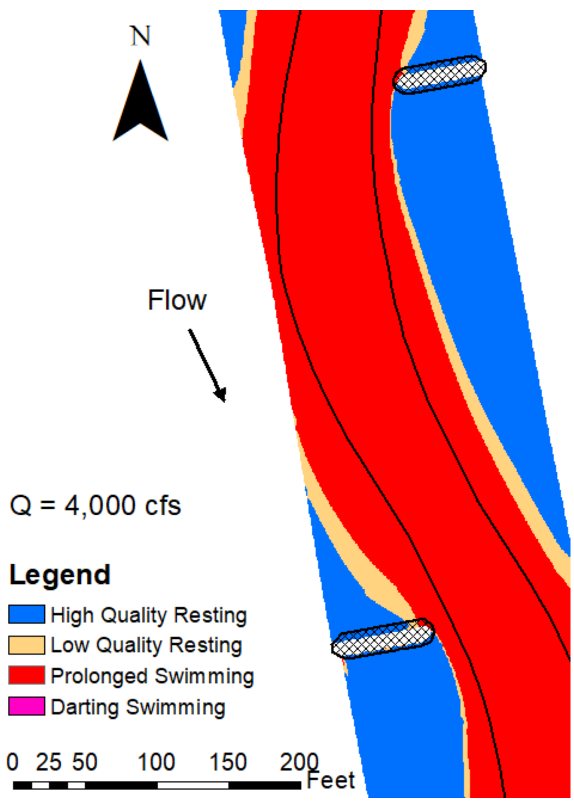

Figure 19. Velocity classification at 4,000 cfs for Geometry 9 (deflectors outside LFC). Depths less than 1 ft are not shown. Black outline represents meandering LFC top of bank. Black hatching represents footprint of deflectors.

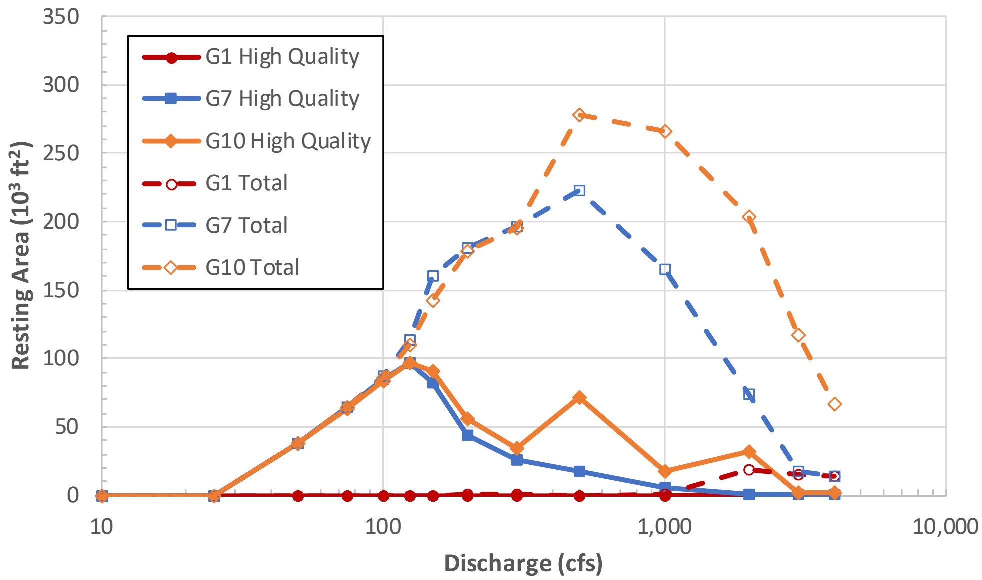

Figure 20. Comparison of high quality (velocity < 3 ft/s and depth > 1 ft) and total (velocity < 5 ft/s and depth > 1 ft) resting area for Geometry 7 (meandering pool-riffle LFC) and Geometry 10 (multi-threaded LFC)

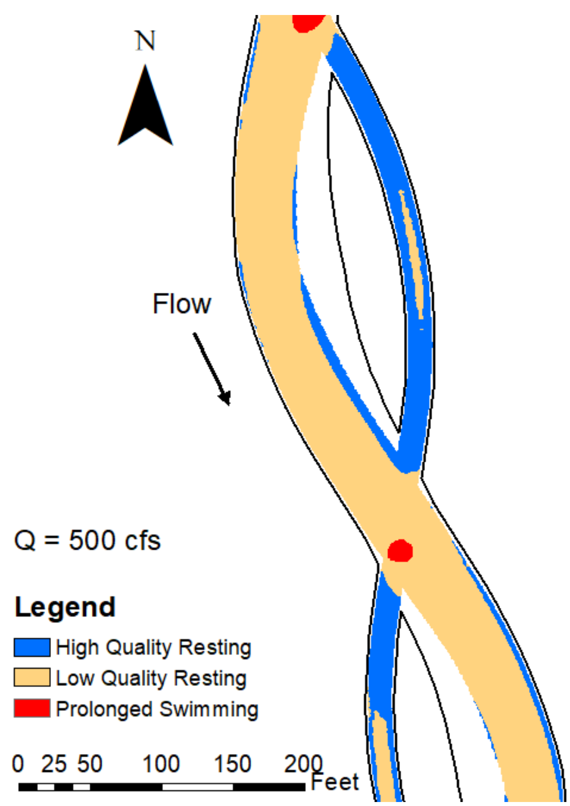

Figure 21. Velocity classification at 500 cfs for Geometry 10 (multi-threaded LFC). Depths less than 1 ft are not shown. Black outline represents multi-threaded LFC top of bank.

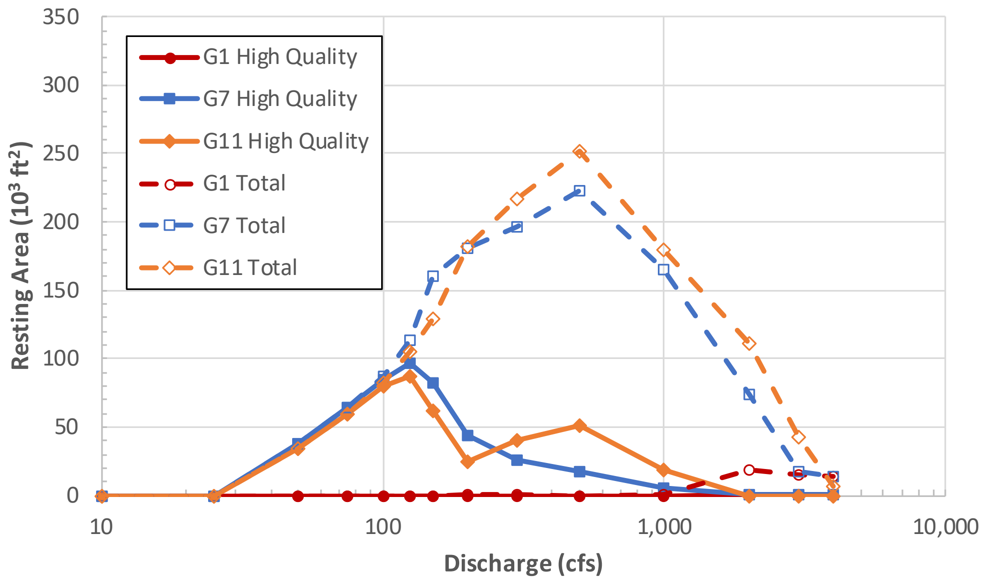

Figure 22. Comparison of high quality (velocity < 3 ft/s and depth > 1 ft) and total (velocity < 5 ft/s and depth > 1 ft) resting area for Geometry 7 (meandering pool-riffle LFC) and Geometry 11 (backwaters)

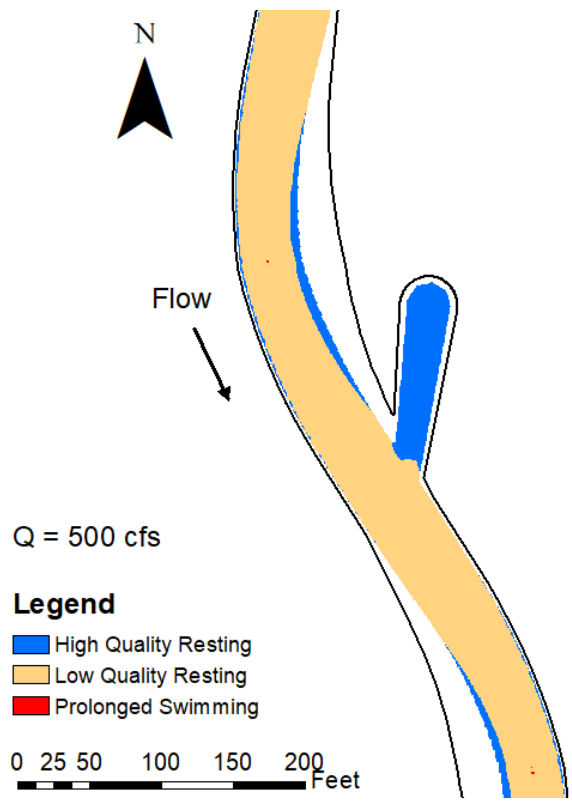

Figure 23. Velocity classification at 500 cfs for Geometry 11 (backwaters). Depths less than 1 ft are not shown. Black outline represents meandering LFC and backwaters top of bank.

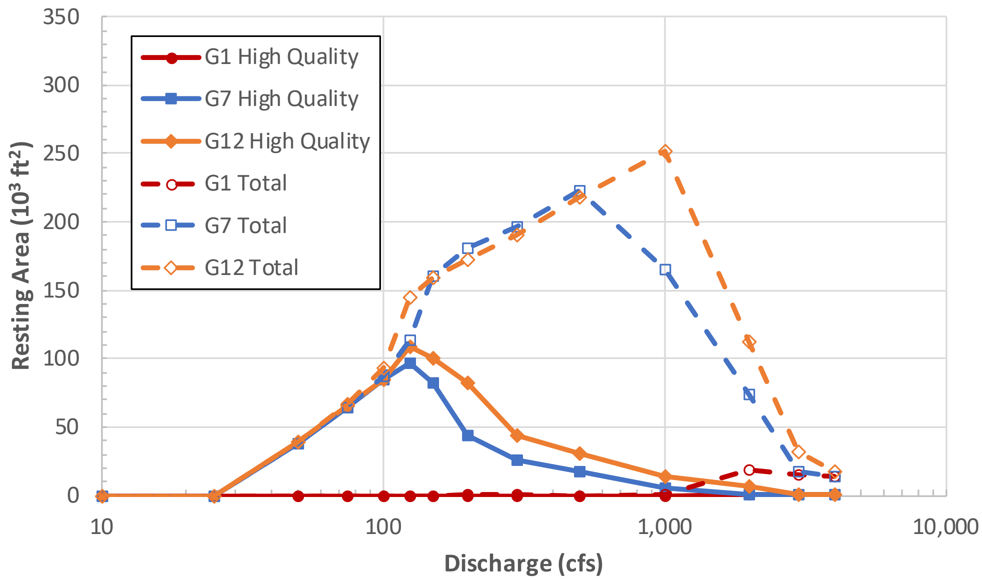

Figure 24. Comparison of high quality (velocity < 3 ft/s and depth > 1 ft) and total (velocity < 5 ft/s and depth > 1 ft) resting area for Geometry 7 (meandering pool-riffle LFC) and Geometry 12 (boulder clusters within LFC)

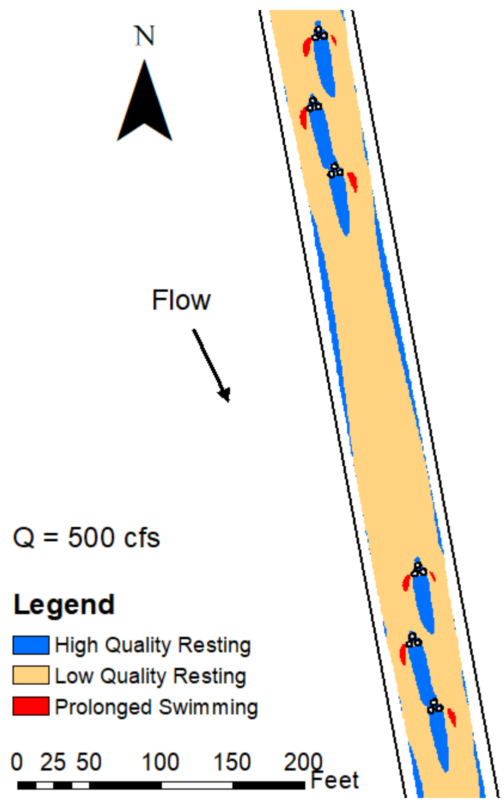

Figure 25. Velocity classification at 500 cfs for Geometry 12 (boulder clusters within LFC). Depths less than 1 ft are not shown. Black outline represents pool-riffle LFC top of bank. Boulder clusters consist of three "upstream V" configurations per riffle with three rocks per cluster.

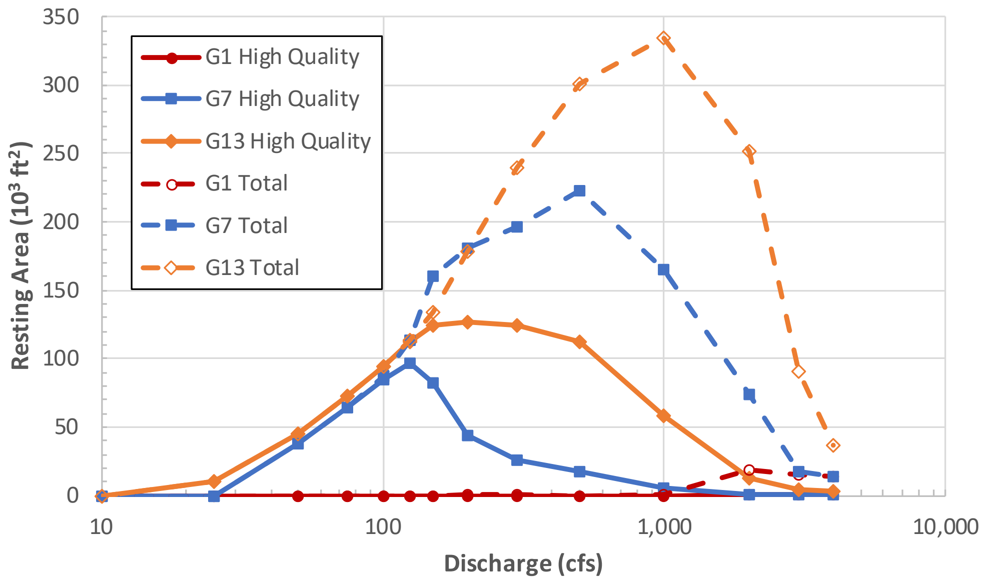

Figure 26. Comparison of high quality (velocity < 3 ft/s and depth > 1 ft) and total (velocity < 5 ft/s and depth > 1 ft) resting area for Geometry 7 (meandering pool-riffle LFC) and Geometry 13 (mid-channel islands and alternating bars within LFC)

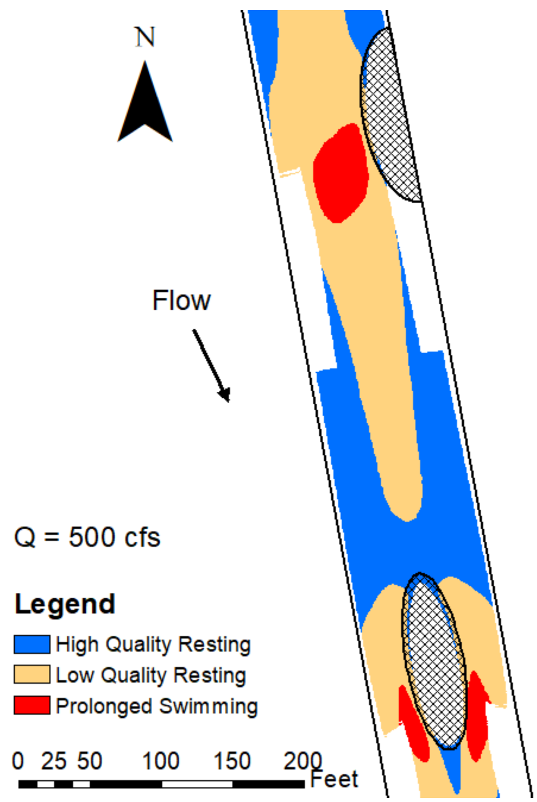

Figure 27. Velocity classification at 500 cfs for Geometry 13 (mid-channel islands and alternating bars within LFC). Depths less than 1 ft are not shown. Black outline represents pool-riffle LFC top of bank. Black hatching represents footprint of islands and bars at channel bed.

Flood Stage

Water surface elevations are compared at the 100-year discharge of 109,000 cfs. Initial simulations use the same roughness values as for the fish passage analysis (Table 4) and then a sensitivity analysis is performed by varying roughness for the existing channel and one design alternative. Figure 28 shows results at a representative cross section near the middle of the subreach assessed for fish passage using the original roughness values. Flow is well within the channel banks for all geometry scenarios with at least 10 ft of freeboard. Figure 29 presents the same results as a column chart so that differences between scenarios are more evident. There is generally a 2 to 4 ft rise in water surface for the various design options. This indicates that the increased width and depth of the LFC is not quite proportional to the increased roughness at the 100-year flow. However, it is likely that the modeled water surface differential is conservative because the effective channel roughness at 109,000 cfs will not be the same as for discharges of less than 4,000 cfs.

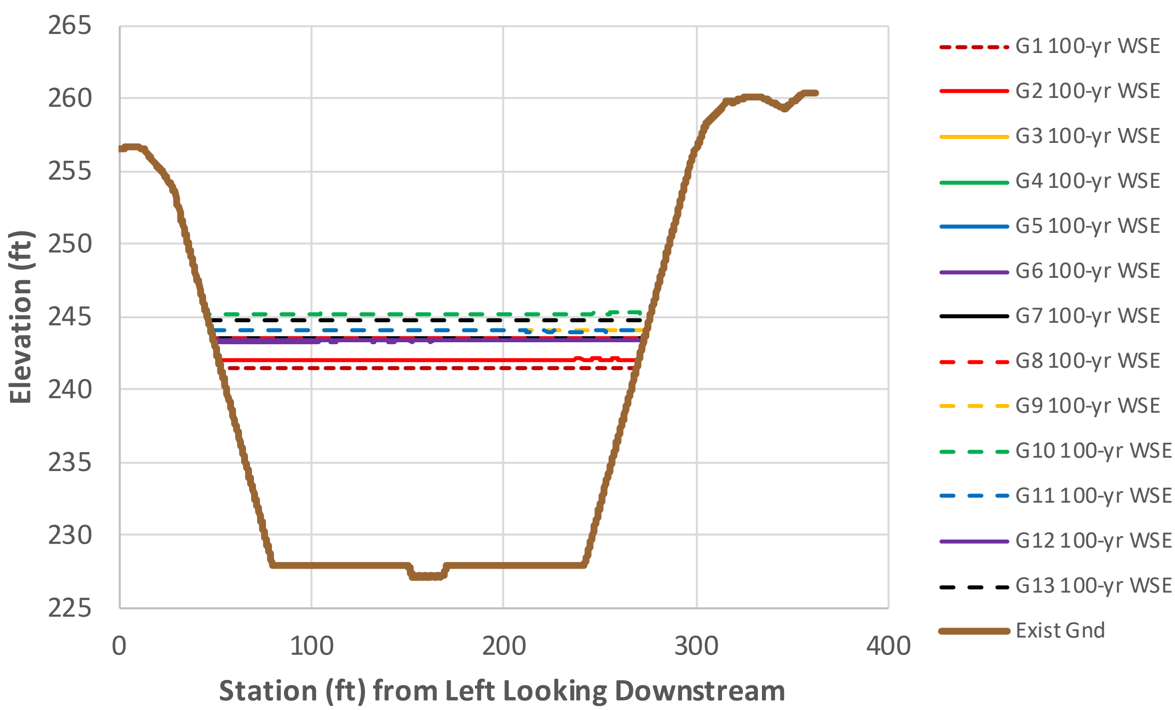

Figure 28. Representative cross section near 4th Street showing water levels for each geometry scenario at the 100-year flow (109,000 cfs). Results are for the same roughness values as used in the fish passage simulations (Table 4).

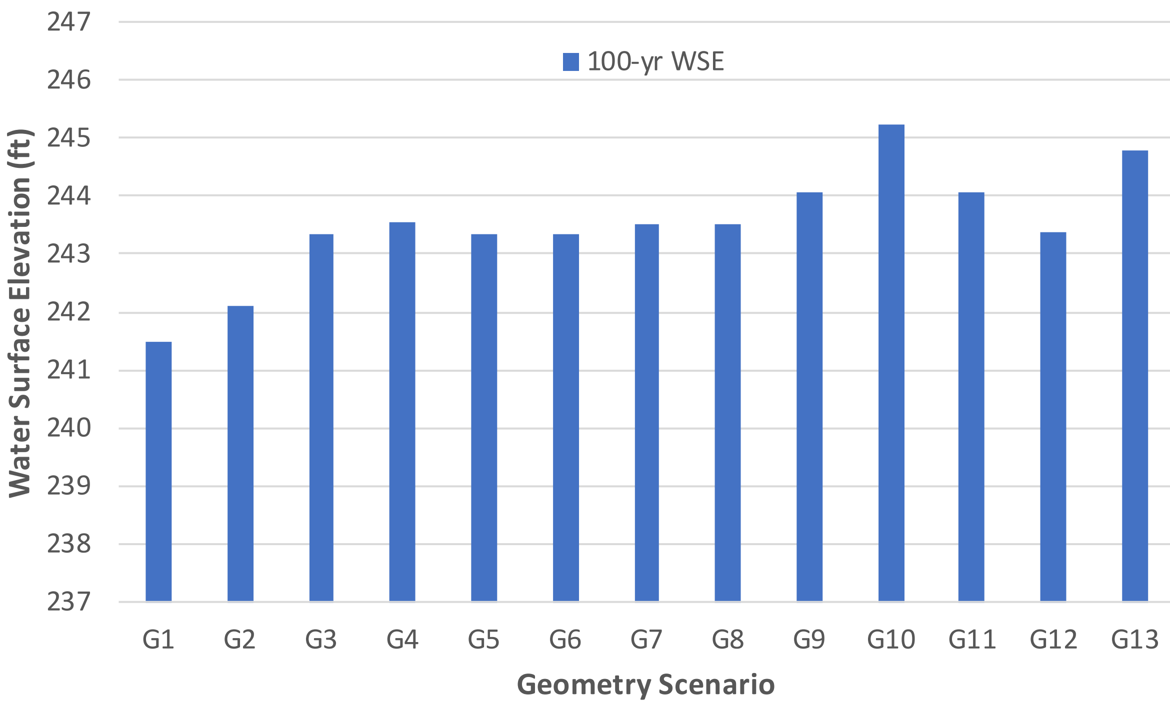

Figure 29. Comparison of water surface elevation at the 100-year flow (109,000 cfs) for the 13 geometry scenarios at a representative cross section near 4th Street. Results are for the same roughness values as used in the fish passage simulations (Table 4).

It is well documented that main channel roughness typically decreases as river discharge and stage increase (e.g., Kim, 2010; Ferguson, 2010; Cheng, 2015). As the ratio of flow depth relative to the height of roughness elements increases above 10, the influence of the bed material particles on bulk hydraulic properties decreases. The relative roughness of cobbles, boulders, and lightly vegetated islands would likely be reduced at the 100-year flow, where depths are about 15 ft, compared to the fish passage flows previously modeled. Conversely, energy losses and frictional resistance may slightly increase at the 100-year flow for the existing channel due to debris and other objects in the river. The river would essentially be operating as a flume at this discharge where flow is supercritical, relatively uniform, and the effect of any low-flow design features would be small.

Model results of a large confined flow are sensitive to the assumed roughness value. Figure 30 presents a sensitivity analysis where roughness is varied for both the concrete portion of the channel and the bed of the designed low-flow channel. Three roughness values are simulated for each material type and results are compared for the existing channel and Geometry 7 (meandering pool-riffle LFC). Water surface in the existing channel increases by about 1 ft with an increase of 0.002 in Manning's roughness. The water surface for Geometry 7 is within 0.1 ft of that predicted for the existing channel if the cobble roughness zone in the LFC is reduced from 0.035 to 0.02. Further research and sensitivity testing of high flow roughness values is recommended during later design phases.

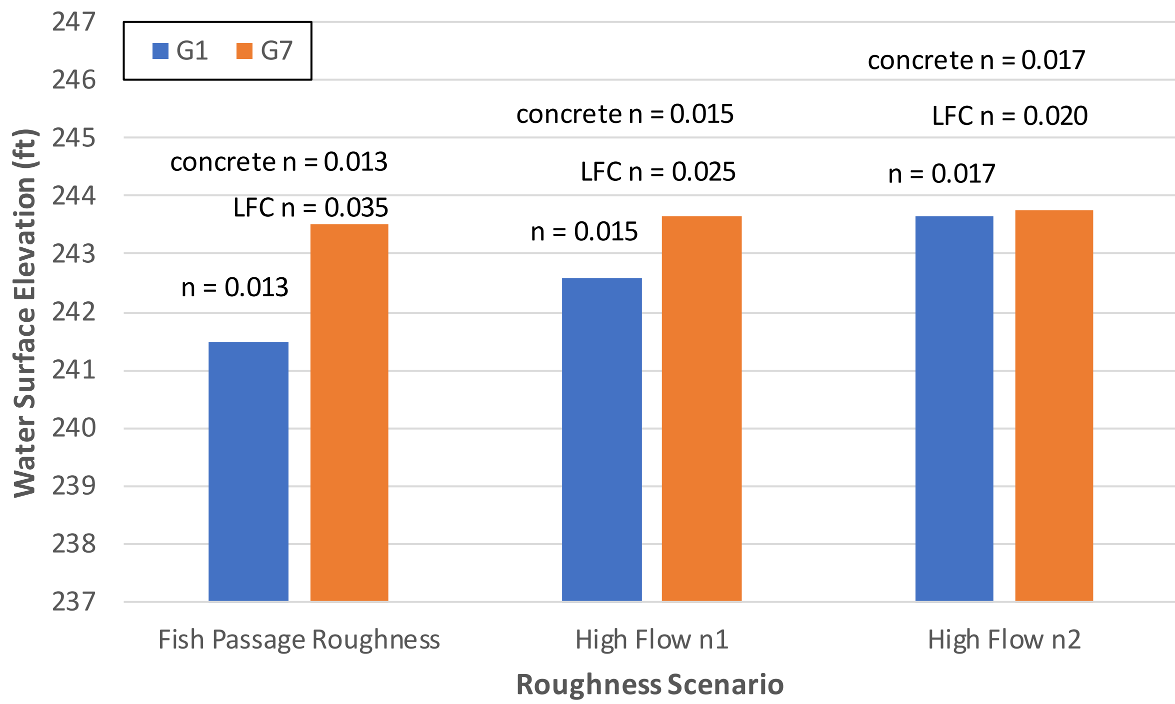

Figure 30. Comparison of water surface elevation at the 100-year flow (109,000 cfs) for Geometry 1 (existing channel) and Geometry 7 (meandering pool-riffle LFC). Sensitivity is assessed for three different roughness scenarios.

Physical Modeling

Model Design

A distorted scale physical hydraulic model with a 1:8 horizontal scale and a 1:4 vertical scale was constructed at the Bureau of Reclamation's Hydraulics Laboratory in Denver, CO. The physical model was scaled to represent the low-flow channel for Geometry 6 (see Table 3 and Figure 7 above) with prototype dimensions of 64 ft wide and about 2 ft deep. The physical model included a roughened channel bed and several sequences of pools and riffles. The full cross section of the flood control channel was not represented in the physical model because the scale of the low-flow channel riverbed features would be too small to provide meaningful results. The focus of the physical model was evaluation of three-dimensional flow features such as boulders and boulder clusters to decrease channel velocity, provide low velocity areas for migrating fish, and increase hydraulic variability.

Distorted Scale

Due to the shallow flow depth at the prototype pilot site, a distorted Froude-scale was selected. A vertically-distorted model scale allows river models more depth while fitting within the physical constraints of laboratory floor space. The increase in water depth minimizes surface tension and viscous effects as these forces can play a disproportionate role in smaller physical hydraulic models (Bureau of Reclamation, 1980). In distorted models with large distortion ratios (i.e. horizontal scale significantly larger than vertical scale), velocity directions may not be correctly reproduced, and the distortion may be visibly distracting to observers. Therefore, it is advisable to keep the model distortion ratio (D_r) less than five to ten (Chanson, 1999). For this model the distortion ratio is derived by:

$$D_r = \frac{L_r}{Z_r} = 2$$
$$L_r = Horizontal\ Length\ Scale = 8$$
$$Z_r = Vertical\ Length\ Scale = 4$$

Additionally,

$$Velocity\ Ratio = Z_r^{0.5} = 2$$

$$Discharge\ Scale = D_r^{\frac{3}{2}} * L_r = 64$$

$$Roughness\ Scale = \frac{D_r^{\frac{2}{3}}}{L_r^{\frac{1}{2}}} = 0.891$$

The low-flow channel roughness designated from numerical modeling was equivalent to that of a natural gravel or cobble stream with a Manning's n value of 0.035. With a distorted model roughness scale of 0.891, the model roughness value was 0.0393. Cobble material was obtained from a local quarry to best estimate the required model roughness.

Model Setup

A physical hydraulic model was constructed using a template system (Figure 31) to fill the gravel bed at the appropriate prototype slope.

Figure 31. Template system used in model construction to ensure changes in slope remained accurate to prototype

Gross dimensions of the model are as follows: top width 11 ft, bottom width 3.75 ft, average slope 0.0089 ft/ft, and a length of 100 ft with 10 ft dedicated to the upstream headbox and 5 ft at the downstream end dedicated to the return channel. For this model, the headbox refers to the area in which the water from the laboratory venturi system enters the model and transitions into open channel flow. Distance along the length of the model was marked using a measuring tape adhered to the side of the channel. Subsequently, the return channel is the area where the water exits the model and returns to the laboratory sump for reuse. The laboratory venturi system comprises of a 12-inch horizontal pump system connected to a 240,000-gallon reservoir. The venturi meters are calibrated using a 44,000 pound (678 ft^3) volumetric/weigh tank to an accuracy of ± 0.25%.

The model depth of this channel varies from approximately 0.375 ft in the riffles, 0.625 ft in the pools, and has an average depth of 0.5 ft (Figure 32). A profile of the pool-riffle sequence is shown in Figure 33. A small section of the flood control channel outside of the low-flow channel (model dimensions of 1.5 ft on each side of the low-flow channel) was included in the model.

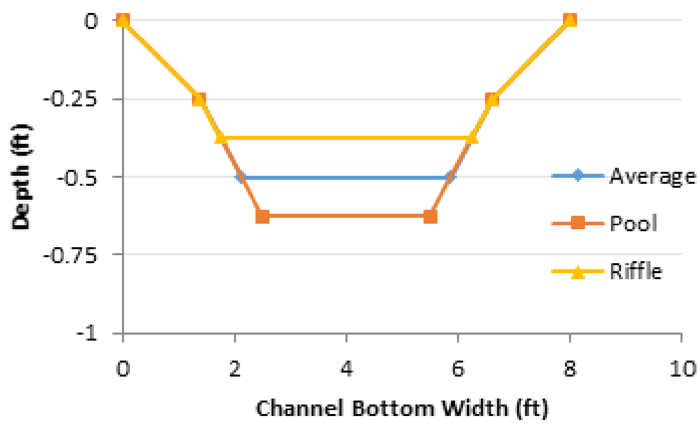

Figure 32. Cross section of compound trapezoid channel showing pool and riffle geometry

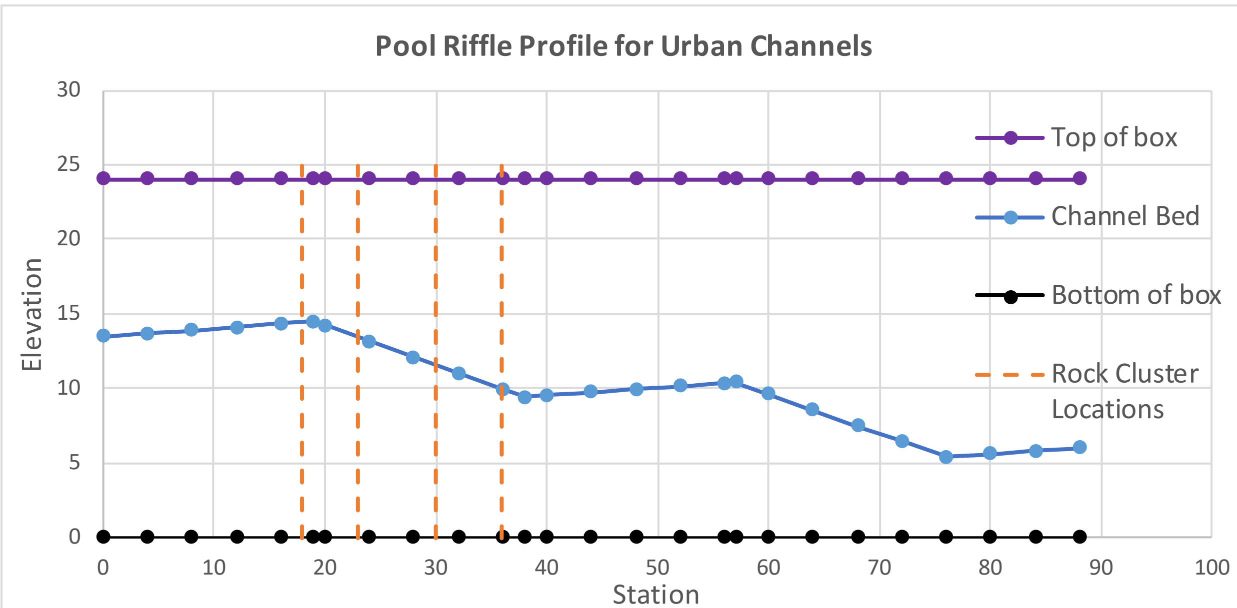

Figure 33. Pool-riffle profile along the length of the physical model

Sampling Techniques

In order to best capture the impact of boulders on the flow field, both an acoustic doppler velocimeter (ADV) and particle image velocimetry (PIV) methods were utilized.

Acoustic Doppler Velocimeter (ADV)

The primary function of the ADV was to take point velocities and depths in a grid around each of the rocks and throughout the channel (Figure 34). The baseline grid consists of four transects and was kept the same for all tests, assuming there was no overlap with boulder clusters. ADV points were added as needed based on the geometry of the cluster to create a grid around each rock. An example of ADV collection locations around a single rock is shown in Figure 35. The utilized grid and results of the point velocity measurements can be viewed in full in Appendix D.

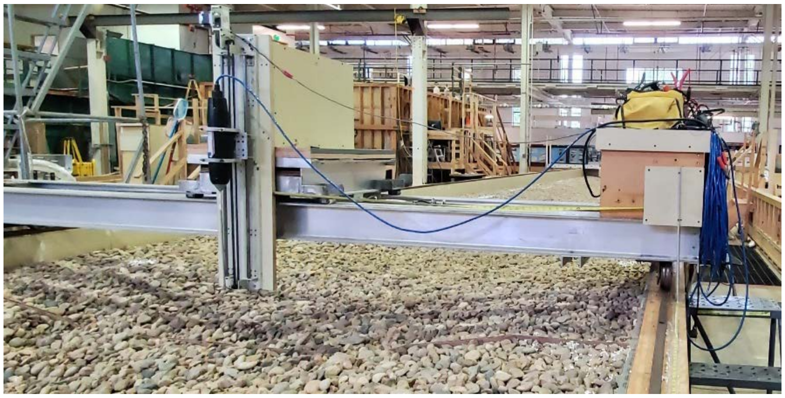

Figure 34. ADV mount in the physical model. The ADV could move horizontally along the length of the model via a traversing system and laterally across the mount by pullies. Additionally, the ADV could move vertically via a stepper motor.

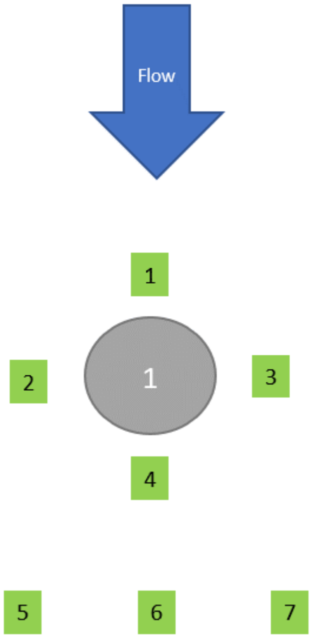

Figure 35. Example of ADV data collection locations around a single boulder

This model utilized a Nortek Vectrino Plus with an N-8513 receiver head. At each point, data were collected for 30 seconds at a sampling rate of 100 Hz and a nominal velocity range of ± 2.5 m/s at approximately 60% of the depth below the water surface elevation to estimate the mean velocity. The ADV requires a 5-cm offset from the bottom of the channel to take an accurate reading without interference from the bottom of the channel. Therefore, water depths less than approximately 8.3 cm could not accommodate an ADV measurement at 60% of the depth without interference from the bottom. When a 60% depth measurement could not be obtained, water column positions at 20% depth were deemed acceptable. Water depth is also recorded alongside ADV measurements in Appendix D.

Samples were collected in Nortek's Vectrino Plus software and processed via WinADV Version 2.031 software (Wahl, 2013). Due to the shallow flow depth outside of the low-flow trapezoidal channel, a lower correlation value of 50% was deemed acceptable.

Large-Scale Particle Image Velocimetry (LSPIV or PIV)

As ADV collection could only process individual points in a grid, LSPIV methodology captured surface velocities for the entire length of the channel test section. To capture this data, a GoPro Hero6 sampled at a rate of 30 frames per second. Seeding material was evenly dispersed into the channel until a minimum of 10 seconds of full coverage within the channel was obtained. Afterwards, frames were separated into individual images using RIVeR 2.2 (Patalano, 2017). These frames were then processed using PIVLab software (Thielicke & Stamhuis, 2014).

PIVLab enabled the user to select a region of interest for post-processing. Within the region of interest, masking could be utilized for specific portions of the test section where data were not relevant. For this model, masking was utilized in locations where reflections on the water surface from overhead lighting caused the software to process these shimmers as faster moving particles, thus producing inaccurate results. Additionally, masks were necessary in regions on the banks of the low-flow channel where water was too shallow to have steady flow. These regions produced askew vectors as the software could not distinguish the flowing water from the shallow, stagnant water. After processing, PIVLab output velocity vector maps of the water surface (Appendix C). These velocity vector maps were saved in ASCII comma separated format and brought into TecPlot Focus to generate banded velocity plots for the specific velocity ranges of interest.

Test Matrix

For this research project, a baseline and four unique rock configurations were utilized at two different flow rates. In the prototype, flow rates were 300 cfs and 600 cfs. The 300 cfs flow rate represents the approximate capacity of the modified low-flow channel before water spills out onto the adjacent concrete. The 600 cfs flow rate represents the maximum flow rate the physical model could reasonably pass without overtopping. At the prototype scale for the full channel cross section, a discharge of 1,000 cfs would have 600 cfs conveyed through the modified low-flow channel and 400 cfs conveyed over the existing concrete bed. Only the low-flow channel is represented in the physical model, so the modeled hydraulics at 600 cfs in the low-flow channel correspond to a river discharge of approximately 1,000 cfs.

Baseline testing comprised of taking velocity readings through ADV and PIV techniques discussed in the "Sampling Techniques" section without any rocks in the channel at 300 cfs and 600 cfs, prototype. The four rock configurations were: single rock, upstream "V", diamond, and downstream "V". The latter three configurations utilize clusters, or groupings of rocks placed in close proximity in the channel (Figure 36).

Figure 36. Single, upstream "V", diamond, and downstream "V" configurations, respectively

The test matrix also comprised of changing the density of the rock clusters. For the cluster configurations, "high density" was defined as 4 clusters, "medium density" was 3 clusters, and "low density" was 2 clusters. For the single rock configurations, "high density" was defined as 8 rocks, "medium-high density" was 6 rocks, "medium density" was 4 rocks, and "low density" was 2 rocks. To minimize impacts from variations in rock shape and sizing, the rocks were kept in the same clusters and in fixed positioning within the clusters. All rocks were selected to be overtopped in the 600 cfs higher flow condition, but not fully submerged. Additionally, the initial four rocks for each cluster during high density cluster configurations were the same initial four rocks used in the medium density for the single rock configuration. These four rocks remained in the same location for each configuration and more rocks were added or taken away as the densities or clusters required (Appendix B).

The location of the first boulder cluster or single rock in the flow for high density configurations was at the top of a riffle with the final boulder cluster or single rock at the bottom of the corresponding pool. As densities moved from highest to lowest, the boulder clusters at the top of the riffle were removed. Therefore, at the lowest density configuration, one cluster remained at the midpoint between the top of the riffle and the bottom of the pool and the second cluster remained at the bottom of the pool. The single rock configuration followed suit with individual rocks dispersed in the same region.

Results

ADV and PIV techniques were employed to gather data which were then analyzed by WinADV, PIVLab, and TecPlot. The full results from each test can be found in Appendix C and Appendix D. As the PIV data performed a more comprehensive view of the entire channel as opposed to the discrete points provided by the ADV, most of the analysis focused on the results from the PIV. However, as PIV collects data from the faster moving surface of the water, this was a conservative approach. ADV data served to highlight trends seen in the PIV data and provide relevant velocities at the 60% depth.

Results were classified according to depth and velocity criteria (see Table 1 and Table 2 above). In-stream cover provided by the boulders may compensate for depths that are shallower than preferred for resting or holding areas. These criteria were applied to all results to find the most effective configuration at the most economical density.

Efficacy of Configurations for Resting Conditions

Roughening the channel with a cobble bed slows down the velocity of the water significantly, however this process alone does not provide high quality resting areas. For the baseline condition at both flow rates, areas with enough velocity to qualify as resting zones only occurred on the banks (Figure 37 and Figure 38). These PIV results were mirrored in the ADV results. As the ADV required an offset from the bottom that was often greater than the depths available on the banks, readings were restricted to within the low-flow channel for the baseline readings. All these ADV points exceeded the resting threshold of 3 ft/s at 60% of the water depth.

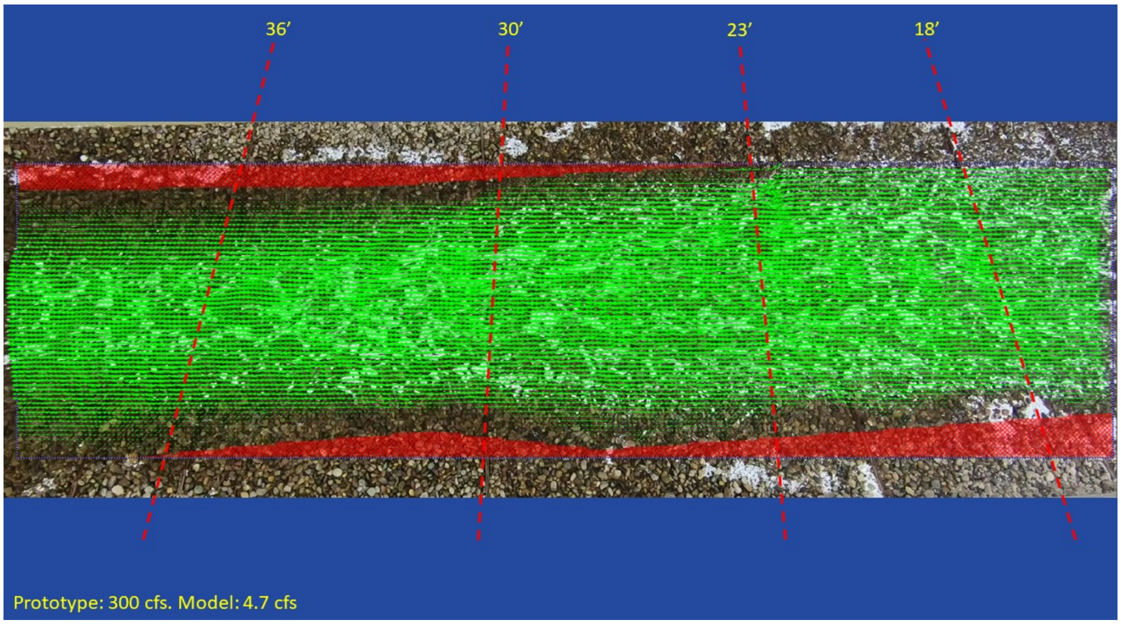

Figure 37. PIVLab output of velocity vectors at 300 cfs baseline flow through the channel. Baseline ADV measurement transects are indicated with dotted lines. Distances marked in figure represent offset downstream from the model headbox. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

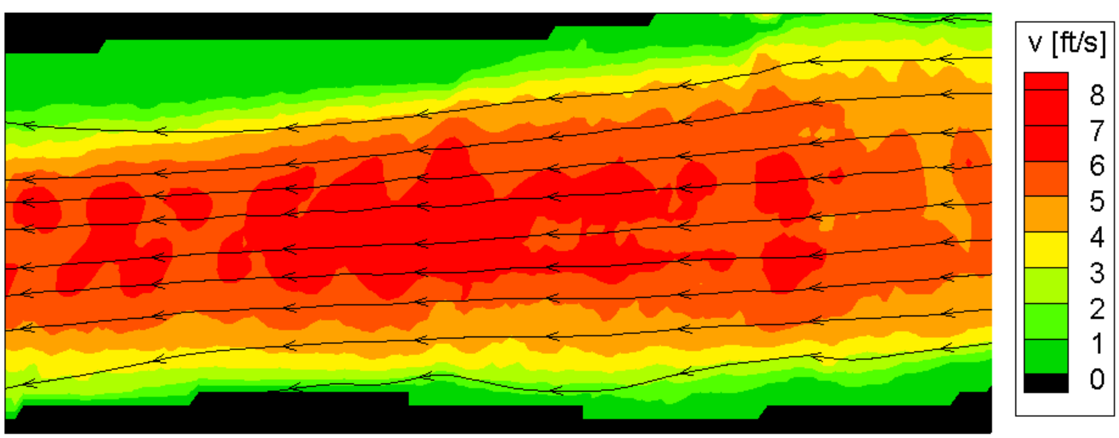

Figure 38. TecPlot output for velocity at 300 cfs baseline flow through the channel. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

Adding rocks sized to be overtopped but not fully submerged for both flow conditions often added suitable resting areas. However, for a single rock at lower and higher densities, this was not always a benefit (Figure 39 and Figure 40). The single rock configuration performed the worst both at 300 cfs and 600 cfs for creating resting areas. To keep the rocks for this configuration truly independent of one another, enabling them to act fully as single rocks, they were spaced as far apart as possible. Due to the trapezoidal nature of the low-flow channel, this spacing caused obstructions that created a shallow area less than the 1-ft requirement, thereby rendering larger sections unsuitable for fish and for analysis with PIV and ADV. This constriction of the channel lowered the fraction suitable for fish passage when compared to baseline area. It should be noted that single rocks may be suitable in wider channels, however this was outside the scope of this investigation and should be considered for future studies.

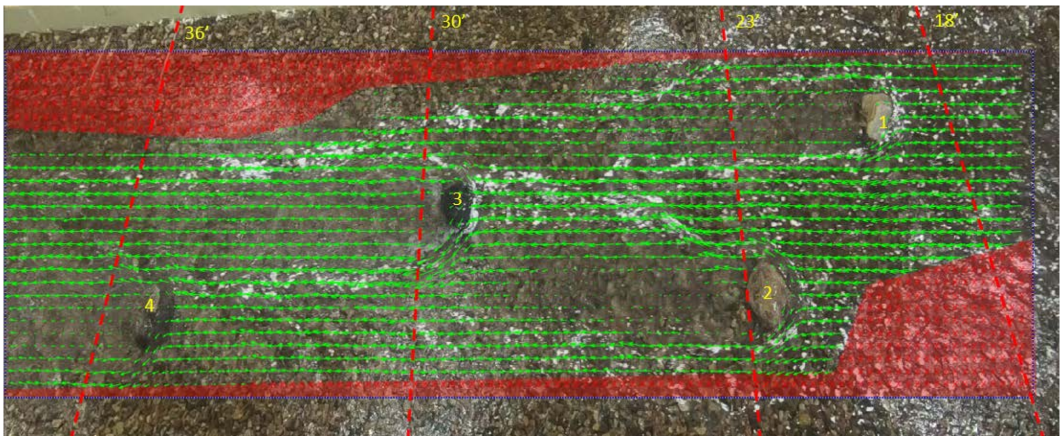

Figure 39. PIVLab output of velocity vectors at 300 cfs for the single rock, medium density configuration. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

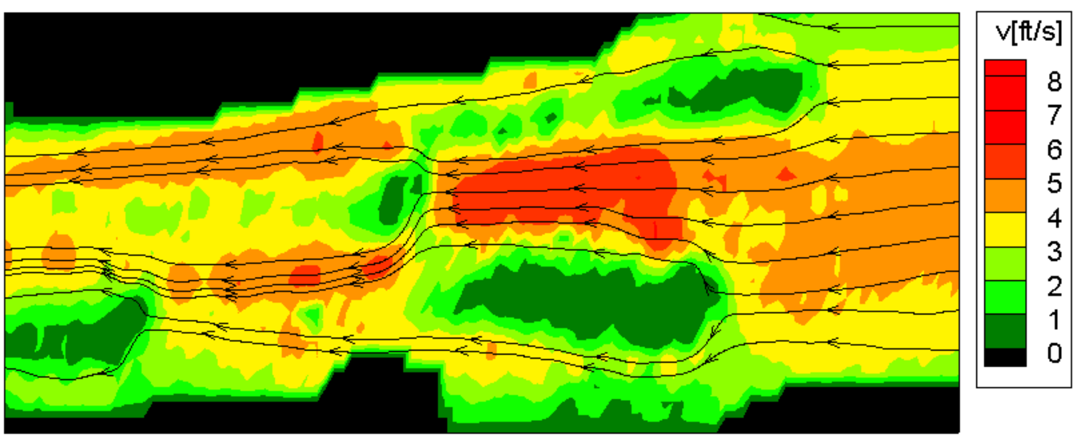

Figure 40. TecPlot output for velocity at 300 cfs at the single rock, medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

While there was no single configuration that provided the highest fraction suitable for all test conditions, on average the upstream “V” and downstream “V” provided the most resting area (Figure 42 and Figure 44). The upstream “V” performed best at higher or lower densities and the downstream "V" performed best compared to any other configuration at medium density. Therefore, the downstream "V" is the most economical option based on the amount of suitable velocity habitat per density of boulder clusters. The cause of the increased fraction suitable is that the downstream "V" created a strong backwater effect, resulting in slower, deeper water upstream of the boulders (Figure 44). Additionally, the downstream "V" had a similar impact as the other boulder cluster configurations in the pool.

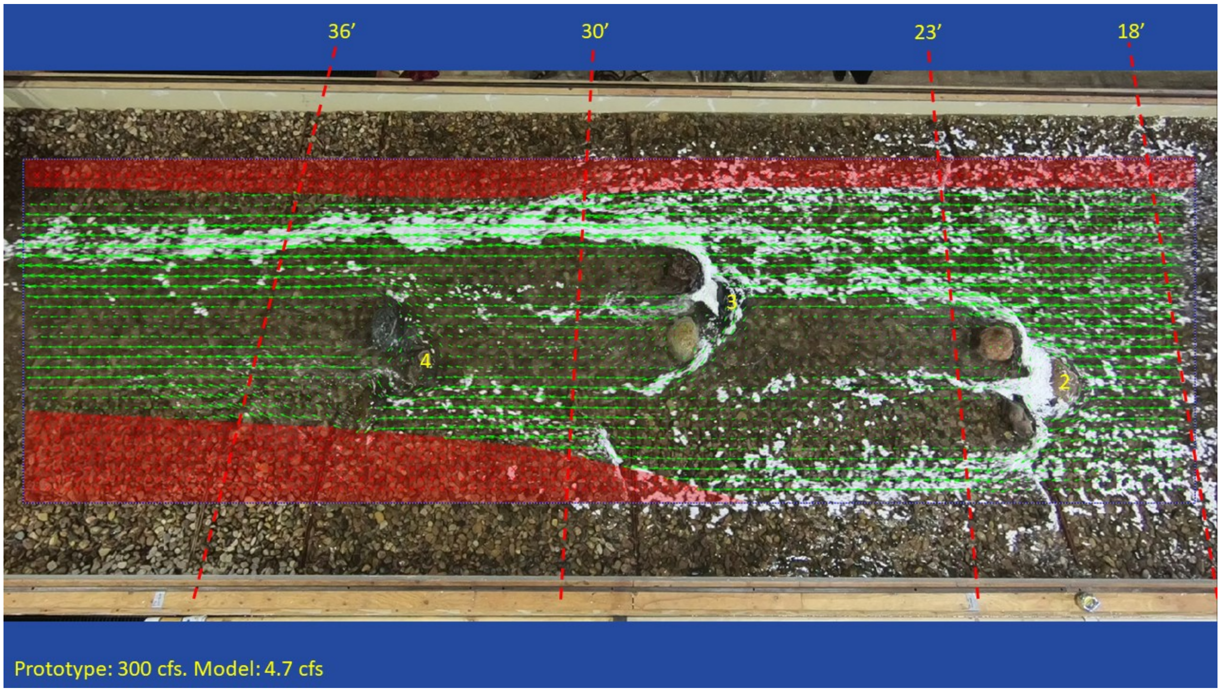

Figure 41. PIVLab output of velocity vectors at 300 cfs at the upstream "V", medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

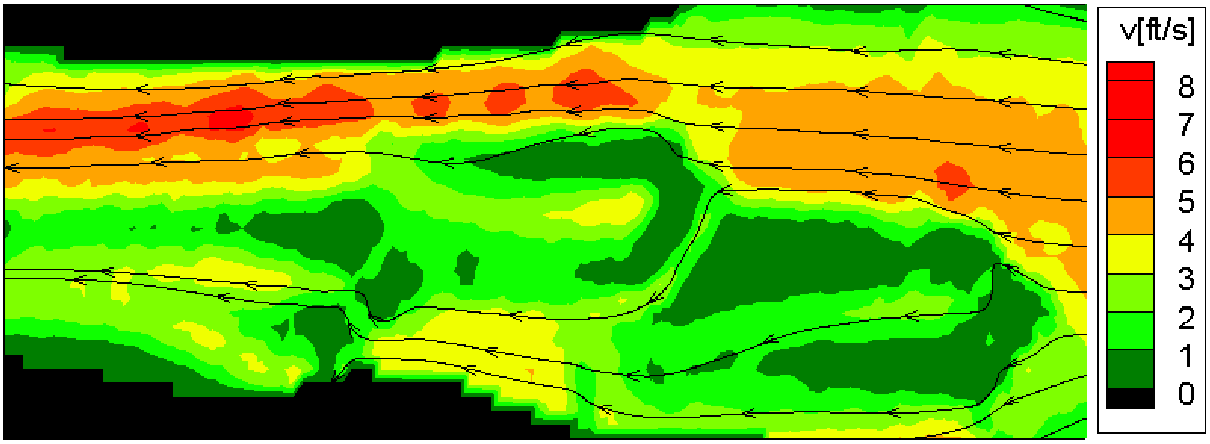

Figure 42. TecPlot output for velocity at 300 cfs at the upstream "V", medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

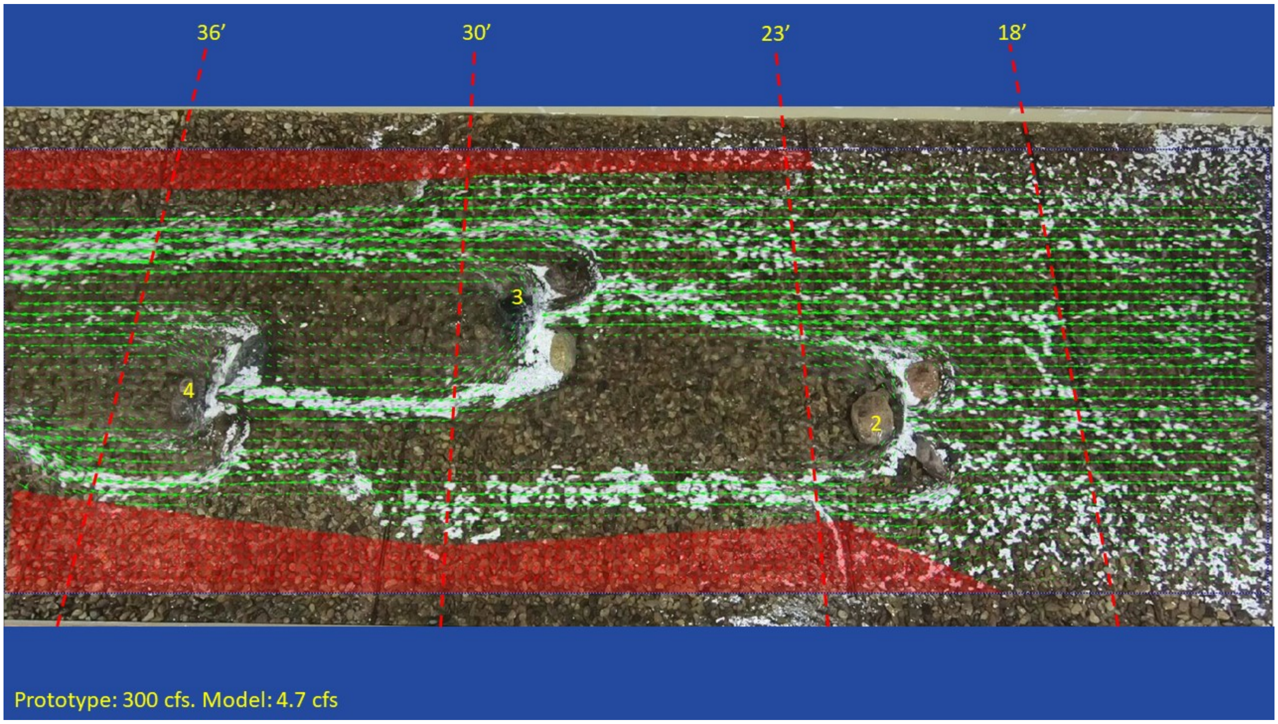

Figure 43. PIVLab output of velocity vectors at 300 cfs at the downstream "V", medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

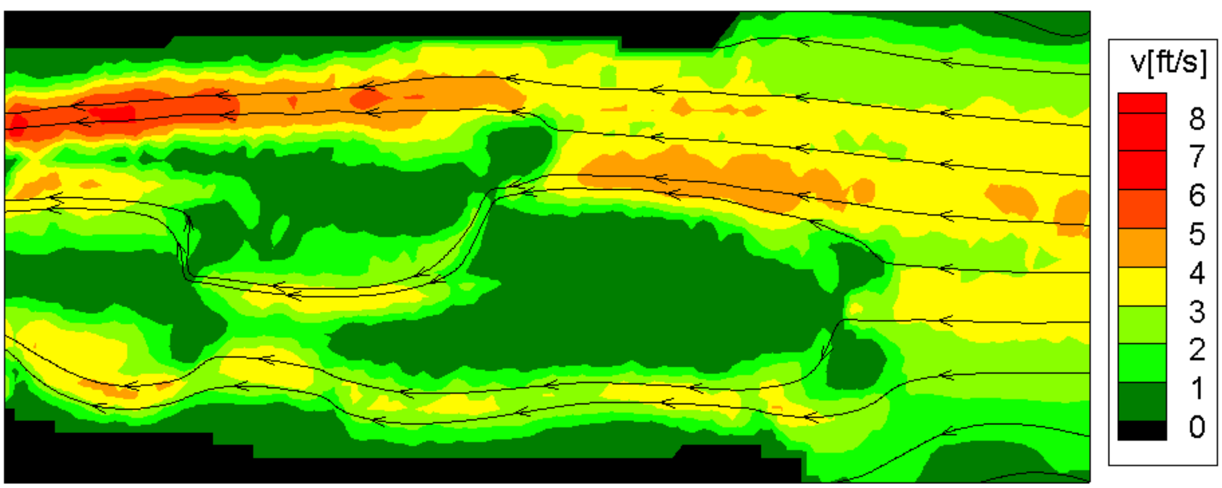

Figure 44. TecPlot output for velocity at 300 cfs at the downstream "V", medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

The diamond configuration performed similarly well, however as it required one additional rock per cluster, it is a less economical solution. Additionally, the diamond configuration increased the number of instances where the water depth was less than the 1-ft threshold for fish passage. This is probably because locations with water depths less than 1 ft were either immediately behind the rocks or in measurement locations on the banks (Figure 46). As the diamond configuration had more rocks, this increases the likelihood of having less than 1 ft water depth, though this was observed independently of cluster density. It should be noted, however that for the 600 cfs flow rate, all water depths at all configurations exceeded the 1-ft threshold. Additionally, some water depths recorded within 0.05-feet of the 1-ft threshold may be acceptable as those readings fall within the margin of error from the ADV.

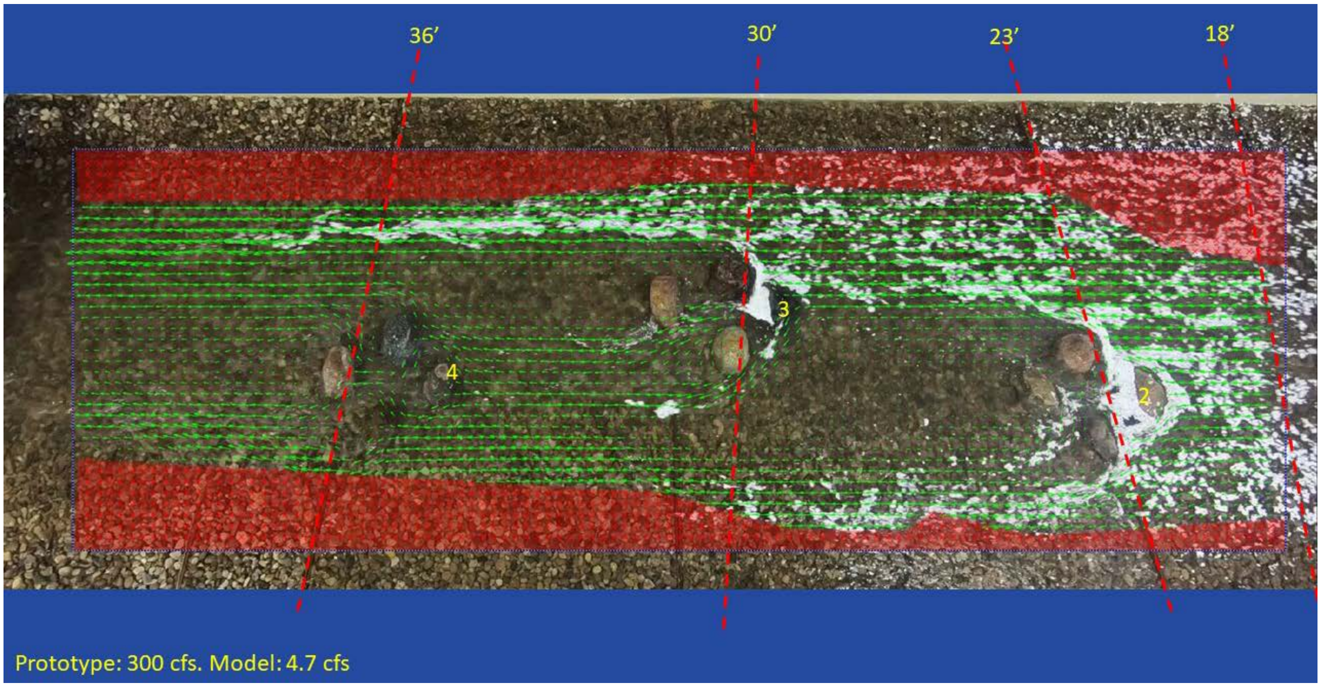

Figure 45. PIVLab output of velocity vectors at 300 cfs at the diamond, medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

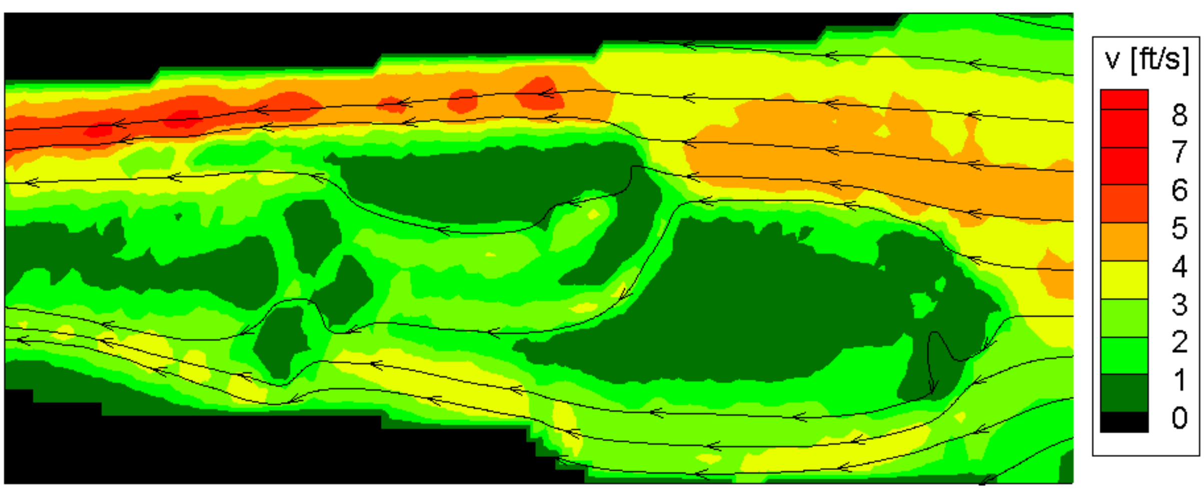

Figure 46. TecPlot output for velocity at 300 cfs at the diamond, medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

After applying the desired velocity suitability criteria to the PIVLab output, the baseline configuration offered 23% fraction suitable for resting at 300 cfs (Figure 47). For the single rock configuration, the percent suitable reached a maximum of 49% at 300 cfs for the medium-high (6 rocks) density. At the lowest efficiency, the single rock configuration obtained 21% fraction suitable for the low (2 rocks) density. The upstream “V” cluster performed at 73% efficiency for the high (4 clusters, 12 rocks) density and in the mid-50% range for both low (2 clusters, 6 rocks) and medium (3 clusters, 9 rocks) densities. This was comparable to the diamond configuration ranging from a 71% fraction suitable at the high (4 clusters, 16 rocks) density to 56% suitable at the low (2 clusters, 8 rocks) density, even though this configuration used an additional rock per cluster. The downstream “V” cluster performed similarly at the high and low densities, however at the medium density (3 clusters, 9 rocks) the configuration peaked to 67% fraction suitable, 10% higher than the upstream “V” for the same amount of rocks, thus performing best for the number of rocks utilized.

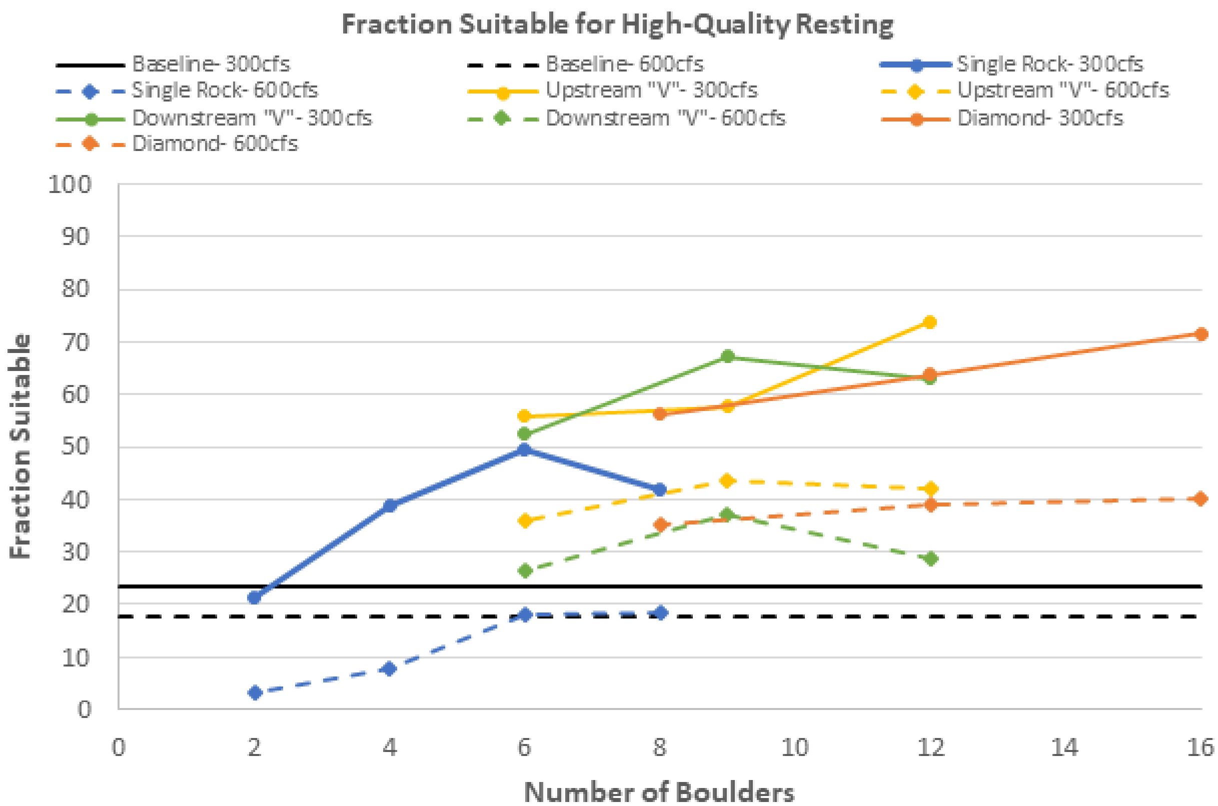

Figure 47. Fraction suitable for high quality resting (< 3 ft/s) versus number of boulders for both the 300 cfs and 600 cfs flow conditions. All 300 cfs tests are denoted as solid lines; 600 cfs are denoted as dotted lines. Matching colors denote the same configuration at the two different flow rates.

Efficacy of Configurations for Low- and High-Quality Resting Conditions

High-quality resting velocities are 0-3 ft/s and low-quality resting velocities are 3-5 ft/s for adult steelhead. Analysis at these conditions highlights the impact of the rocks at slowing the water but not to the extent of high-quality resting. This can be an important distinction if low quality resting velocities are deemed suitable for a potential site where high flows are common.

While most configurations followed a similar pattern as the high quality resting analysis, the single rock configuration performed significantly better at all densities when including total resting (high and low quality). The single rock configuration type compared well to other configurations for total resting area (Figure 48). As opposed to high-quality resting only conditions where single rock configurations peaked at the medium-high (6 rocks) density at 49% suitable, the combined acceptable for the same density was 95% suitable. This 90% range was maintained for all single rock densities except for the lowest density (2 rocks) which was 52% efficient, slightly under the 300 cfs baseline efficiency of 55%. This means that single rocks may reduce fish passage suitability at some locations in the low-flow channel.

Comparing the peak fraction suitable of the medium-high (6 rocks) density to the medium densities of the clustered configurations, all clustered configurations performed above 95% as well but used a minimum of 9 rocks. Such an improvement to the single rock configuration performance implies that if low-quality resting is acceptable, a combination of configurations performs adequately to obtain the goal of creating a high percentage of suitable resting area.

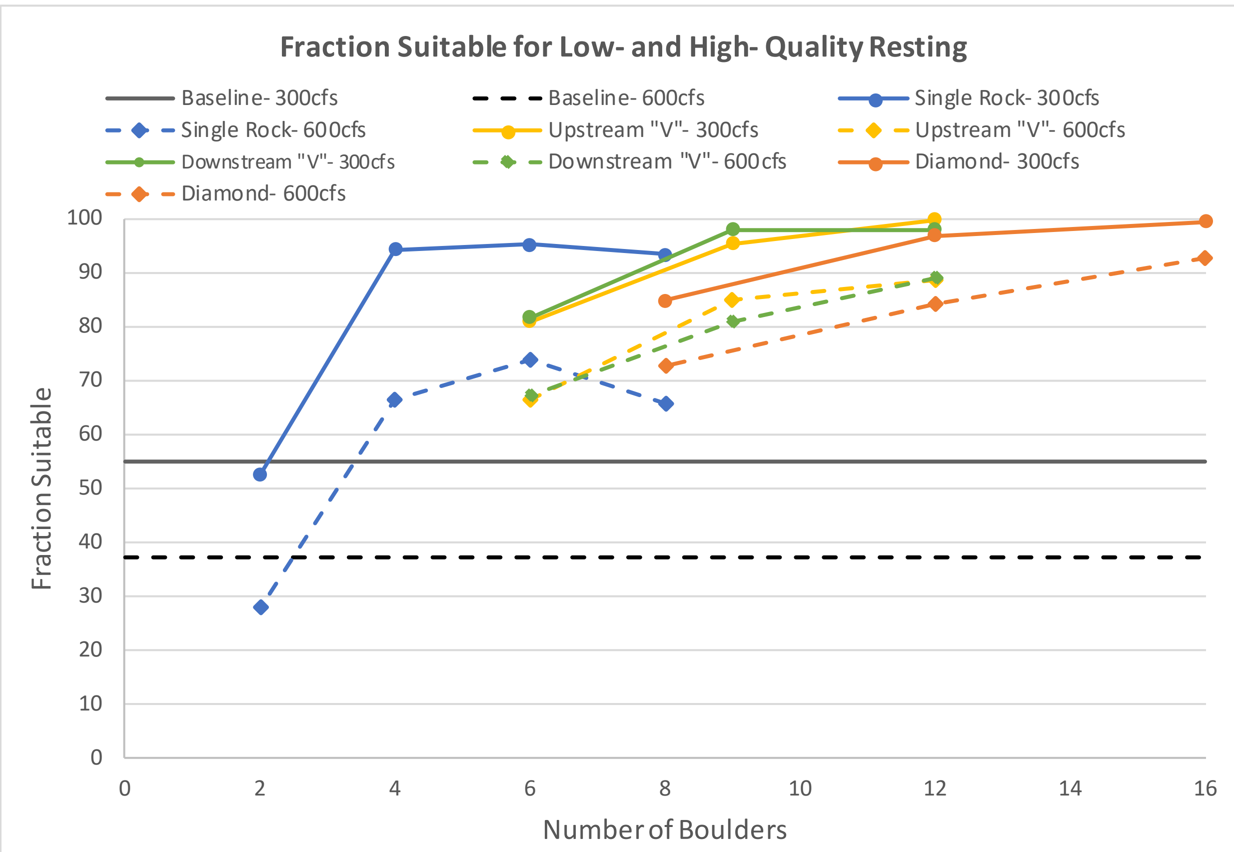

Figure 48. Fraction suitable for low- and high-quality resting conditions (< 5 ft/s) versus number of boulders for both the 300 cfs and 600 cfs flow conditions. All 300 cfs tests are denoted as solid lines; 600cfs are denoted as dotted lines. Matching colors denote the same configuration at the two different flow rates.

Conclusions and Recommendations

Conclusions

A 2D numerical model of the LA River as a pilot site for urban flood control channels provides several insights about existing fish passage limitations and opportunities for improvement. Fish passage was selected as the focal area for this study to improve aquatic habitat because it is often the most realistic goal in heavily modified and developed urban corridors. Providing fish passage and improved longitudinal connectivity for all aquatic organisms through urban river reaches may provide access to higher quality habitat in upstream reaches. This study confirms that concrete lined flood control channels do not provide suitable hydraulic conditions for native fish: depths are too shallow, and velocities are too high. Model results demonstrate that the LA River does not meet fish passage criteria at any flow rate. A deeper and rougher low-flow channel is required to increase depth and reduce velocity within suitable fish passage limits. This channel can be relatively simple and uniform to provide significant benefits at low flows less than about 200 cfs. There are some differences between design alternatives, but all geometry scenarios developed during this study provided similar benefits at these low flows.

Larger scale channel features are needed to provide habitat and fish passage benefits at higher flows. Mid-channel islands and bank-attached bars show the most promise at 300 to 1,000 cfs. This channel planform is consistent with a confined urban river because the bars and islands develop when there is not space for meandering and lateral migration. Providing resting areas for migrating fish at the upper end of fish passage flows (2,000 to 4,000 cfs) likely requires features outside the extent of a low-flow channel. Deflectors tested within the floodplain provide large areas of low velocity zones. Results from boulder cluster models indicate that these features provide useful resting areas of lower velocity. However, boulder placement should be combined with a larger scale feature because the total area occupied by the boulders, and the corresponding effect on the flow field, is relatively small. The potential impact of the various design modifications on flood stage was assessed by modeling the 100-year flow. There will likely be a small increase (less than 2 to 4 ft) in water surface elevation as a result of the design features. This result is sensitive to the assumed roughness values. Sensitivity analysis demonstrates that the increased stage due to design features was less than 0.1 ft under some roughness scenarios. Additional work is needed on quantifying the roughness of design features at flood stage.

A physical model was constructed to further investigate the local hydraulics around boulder clusters. Four configurations were tested in the physical model. These configurations were: single rock, upstream “V”, diamond, and downstream “V’. All configurations presented unique attributes that would be best suited for varying flow conditions. The downstream “V” configuration was highly effective for the number of rocks used by creating a backwater effect upstream of the clusters. However, this backwater area may impinge on channel freeboard requirements. The upstream “V” configuration was better suited for creating both low- and high-quality resting areas at higher flows. Therefore, the upstream “V” configurations may be a reasonable option for channels that are subject to more frequent high flow events where any resting area between 0 and 5 ft/s is considered acceptable. Additionally, single rocks followed a similar pattern where they performed best where low-quality resting conditions are acceptable, posing an economic advantage in high flow channels. The diamond configuration is not as cost-effective compared to the upstream and downstream "V" configurations: these are similarly effective while requiring less rocks. Therefore, rock configurations should be varied based on site-specific conditions such as frequency of high flow events, cost, and freeboard restrictions.

High densities did not consistently produce more resting area due to rocks constricting flow through the channel. However, if low-quality resting conditions are deemed acceptable, higher densities performed better, though still not consistently. Additionally, high densities for the single rock and upstream "V" configurations were successful at keeping water depths above the 1-ft desired threshold for both flow rates. Depths less than 1 ft were seen in all configurations either immediately behind select rocks where highly turbulent recirculating flows are common or when rocks, whether in clusters or as a single unit, were positioned on the side slopes of the low-flow channel as they were too close to the banks.

Further studies are needed to clearly assess the performance of single rock configurations in wider channels. Wider channels would enable single rocks to be placed in the channel without interfering with one another or constricting the flow. It is also advisable to test other alternatives to rocks, such as flow deflectors. Finally, all configurations tested in this study occupied the top of the riffle to the bottom of the corresponding pool. This may have impacted the efficacy of the lower clusters at creating resting areas, although no clear patterns emerged. More studies need to be carried out to investigate a longer reach of channel where all clusters can be placed only at the top of the riffle where rocks are less likely to be overtopped by higher flow rates.

Recommendations for Next Steps

Fish passage analysis can be further refined by implementing multiple depth criteria rather than a single threshold. For example, passage may be possible for short distances at depths as low as 0.5 or 0.8 ft. High quality resting or holding habitat likely requires a depth of at least 1.5 or 2 ft. Channel design geometry can be developed to more specifically target these depths. A narrower low-flow bottom width may be needed to achieve full connectivity at the minimum depth threshold.

A next step for design is to develop combinations of different features or increased variability of a certain type of feature. Designs developed during this study were intentionally uniform so that major types of alternatives could be compared. A mosaic of different types and sizes of islands, bars, and boulders would likely provide benefits across a wider range of flows.

There is uncertainty in the roughness values of design features across the range of low to high discharge. Additional research and sensitivity modeling are recommended to develop more accurate roughness values and understand the potential effects of changes to the roughness, especially if there is little tolerance for a small rise in water surface elevation at flood stage.

More information can be gathered from additional physical model testing of boulder configurations. Testing at a lower density, such as a single boulder cluster, would provide better definition to the suitability curve. Additional arrangements of boulders and different installation locations laterally across the channel and longitudinally within a pool-riffle sequence would expand the applicability of test results. Finally, the data from the boulder physical model tests should be compared with a 2D numerical model. Figure 49 shows that the numerical model is qualitatively representing the correct flow field caused by the boulders. The next step is to test the numerical model for various laboratory configurations and determine the best approach for quantitatively matching the measured depth and velocity values. It will not often be possible to test boulder configurations in a physical model to assess project specific designs. There would be significant value to having confidence in a 2D numerical model to simulate the complex hydraulics associated with boulder clusters.

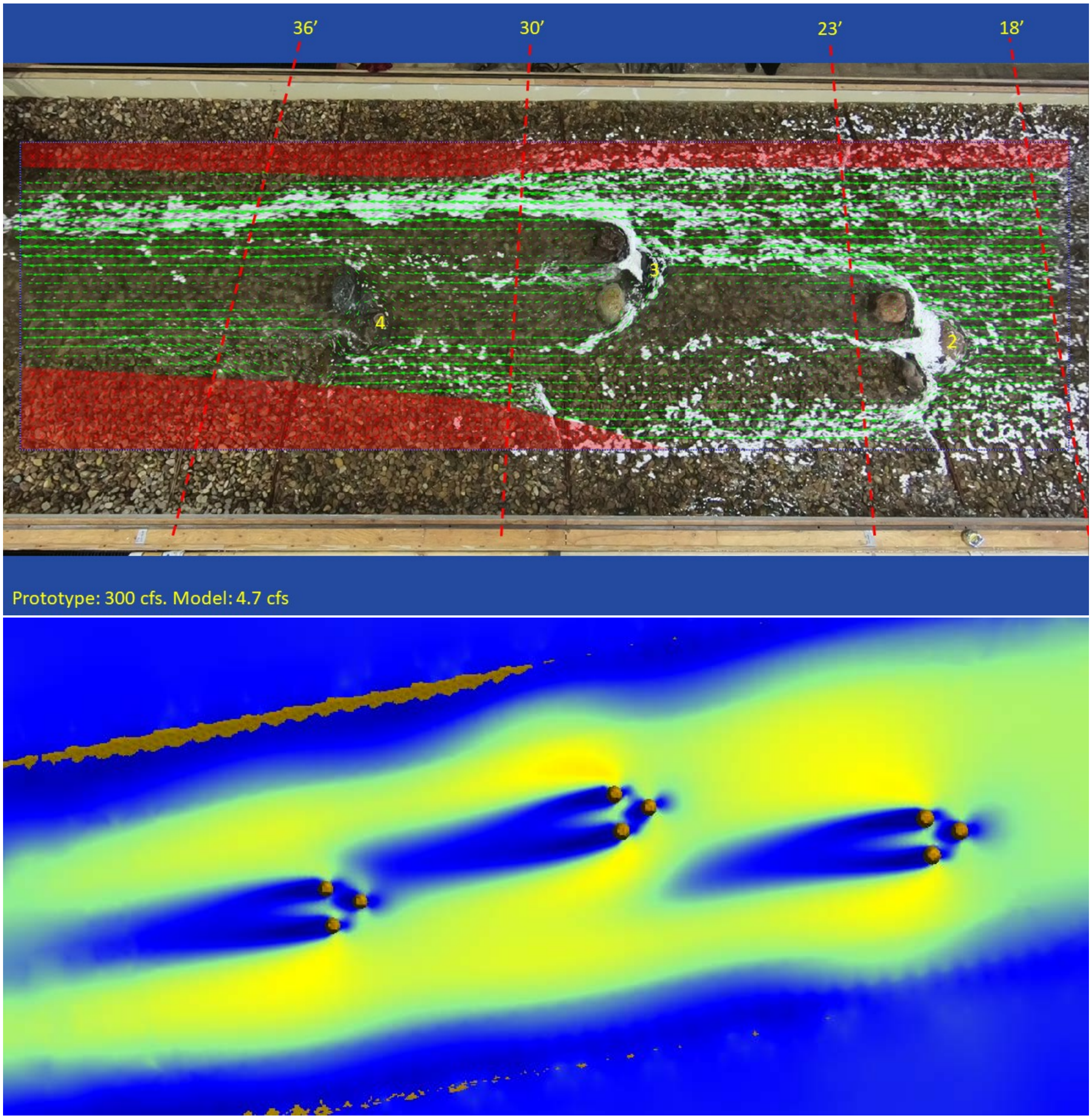

Figure 49. Comparison of velocity field at 300 cfs for physical model at lab scale (top) and numerical model at prototype scale (bottom). Flow is right to left.

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Appendix A – Select Velocity Maps from 2D Numerical Model

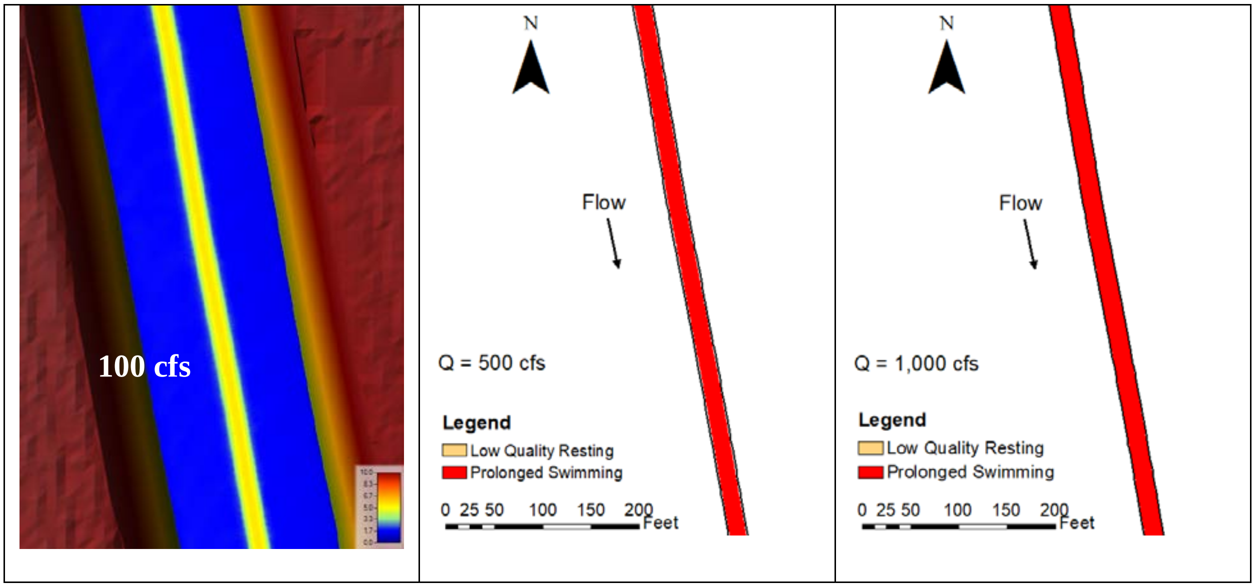

Figure A 1. Existing channel (G1) velocity map at 100 cfs (left), 500 cfs (center), and 1,000 cfs (right). Velocity for all depths is shown at 100 cfs. Velocity classification is only shown for depths greater than 1 ft at 500 cfs and 1,000 cfs.

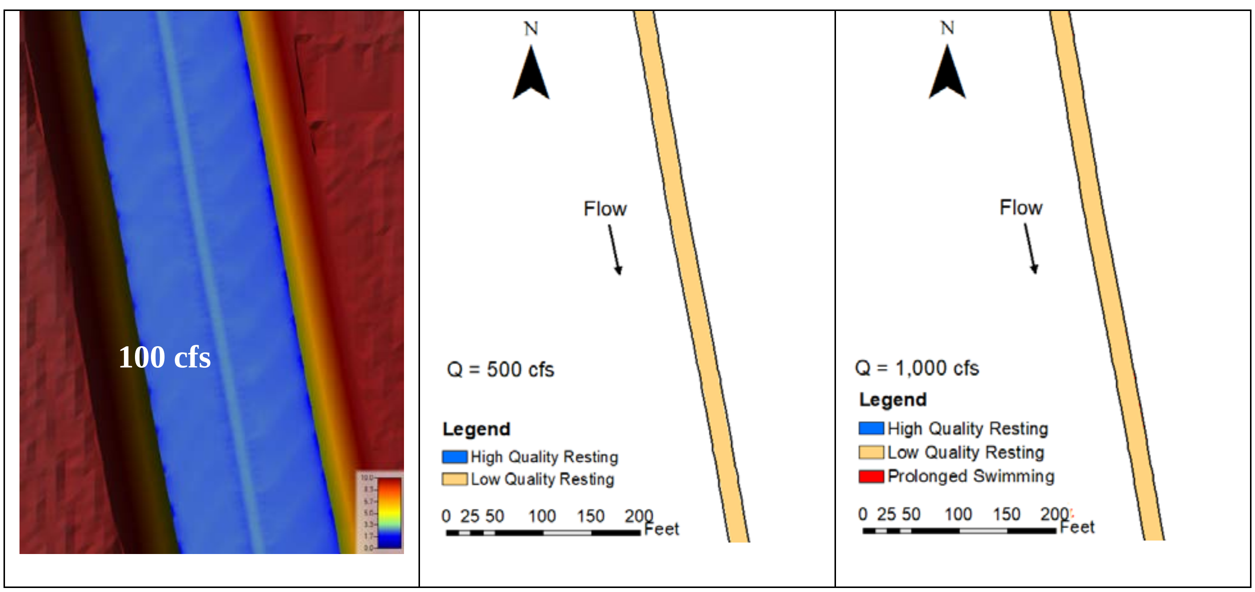

Figure A 2. Existing channel with roughened LFC (G2) velocity map at 100 cfs (left), 500 cfs (center), and 1,000 cfs (right). Velocity for all depths is shown at 100 cfs. Velocity classification is only shown for depths greater than 1 ft at 500 cfs and 1,000 cfs.

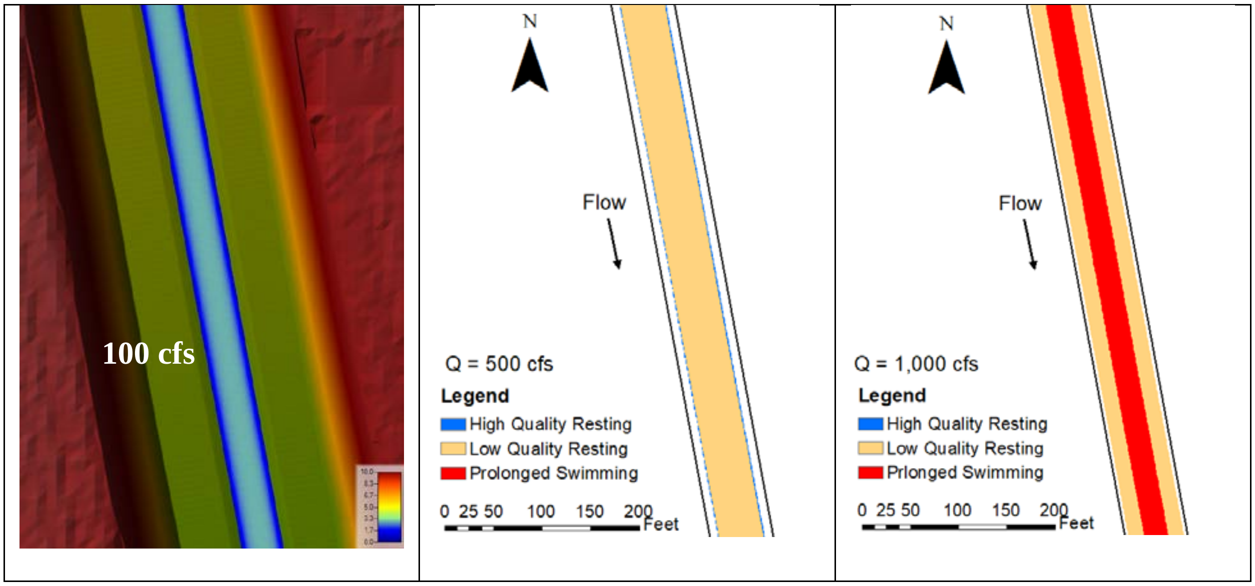

Figure A 3. Increased width and depth LFC (G3) velocity map at 100 cfs (left), 500 cfs (center), and 1,000 cfs (right). Velocity for all depths is shown at 100 cfs. Velocity classification is only shown for depths greater than 1 ft at 500 cfs and 1,000 cfs.

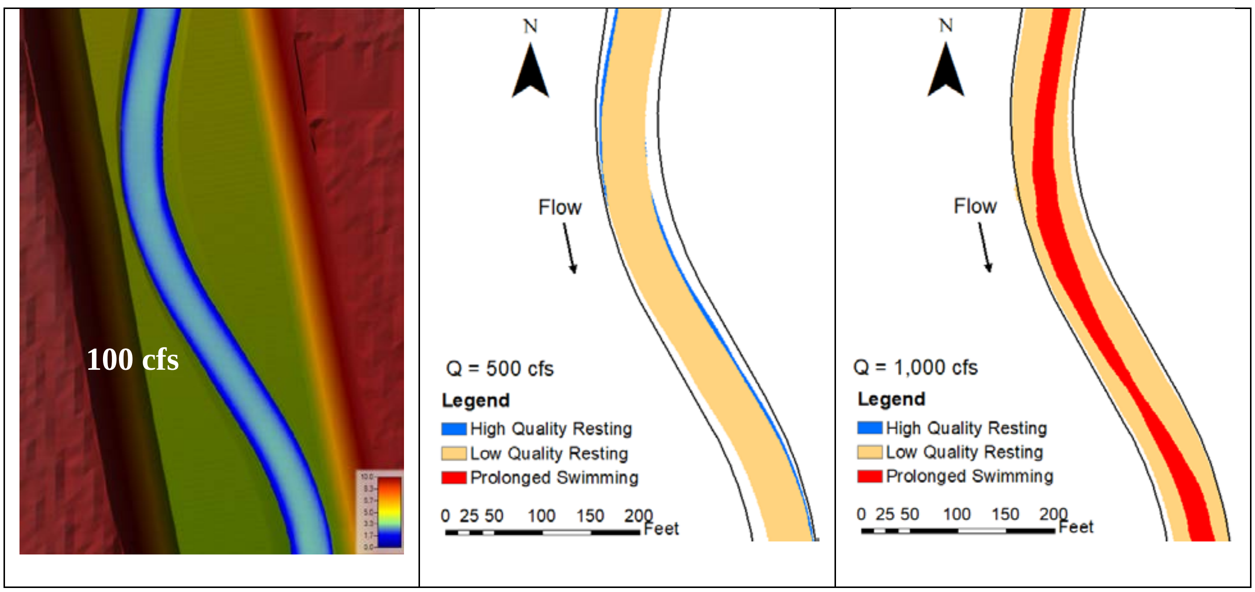

Figure A 4. Meandering LFC (G4) velocity map at 100 cfs (left), 500 cfs (center), and 1,000 cfs (right). Velocity for all depths is shown at 100 cfs. Velocity classification is only shown for depths greater than 1 ft at 500 cfs and 1,000 cfs.

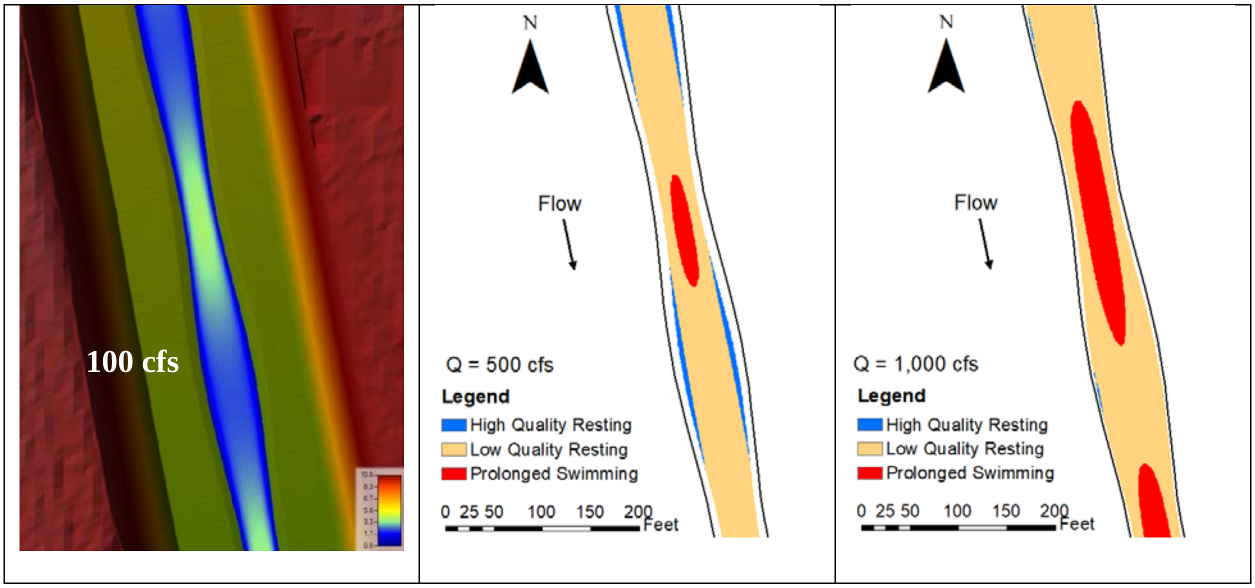

Figure A 5. Variable width LFC (G5) velocity map at 100 cfs (left), 500 cfs (center), and 1,000 cfs (right). Velocity for all depths is shown at 100 cfs. Velocity classification is only shown for depths greater than 1 ft at 500 cfs and 1,000 cfs.

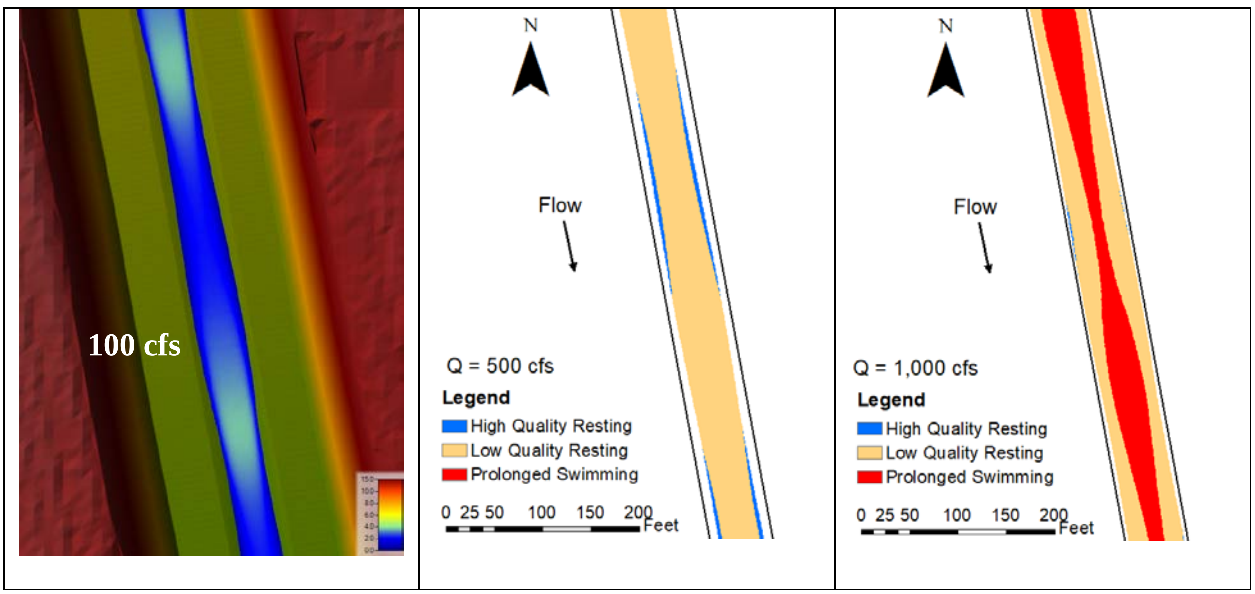

Figure A 6. Pool-riffle LFC (G6) velocity map at 100 cfs (left), 500 cfs (center), and 1,000 cfs (right). Velocity for all depths is shown at 100 cfs. Velocity classification is only shown for depths greater than 1 ft at 500 cfs and 1,000 cfs.

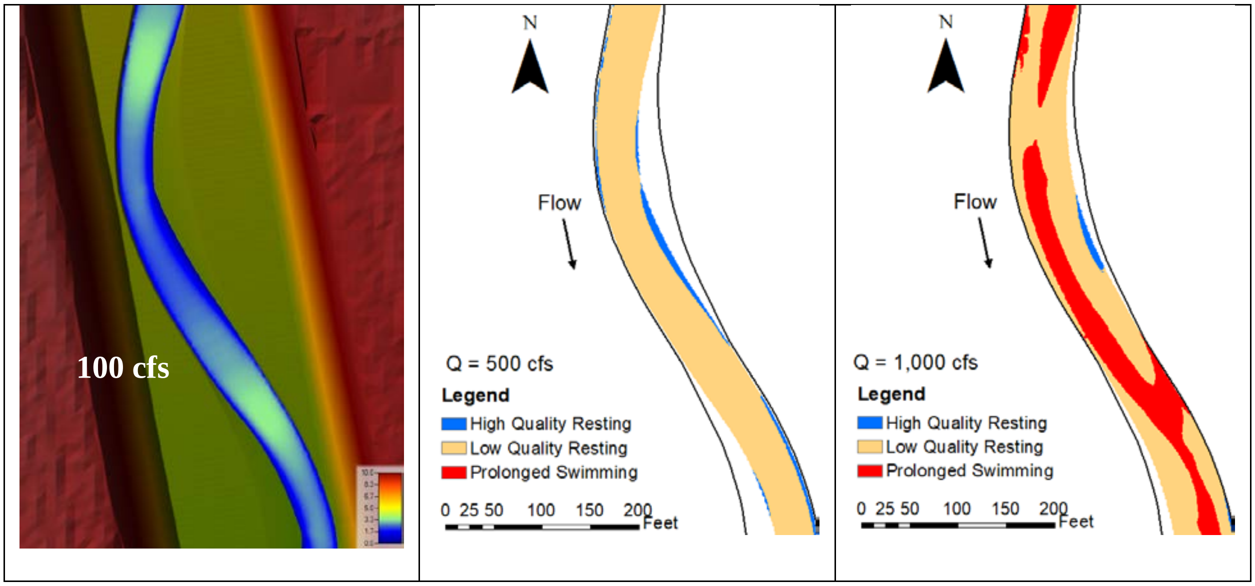

Figure A 7. Meandering pool-riffle LFC (G7) velocity map at 100 cfs (left), 500 cfs (center), and 1,000 cfs (right). Velocity for all depths is shown at 100 cfs. Velocity classification is only shown for depths greater than 1 ft at 500 cfs and 1,000 cfs.

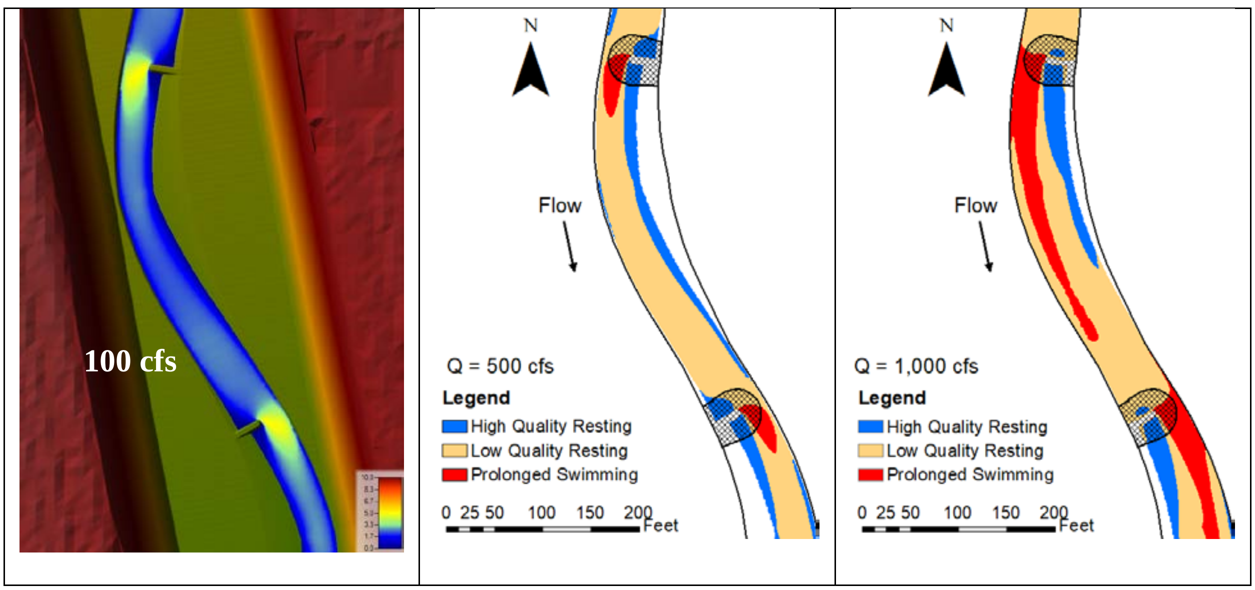

Figure A 8. Deflectors within LFC (G8) velocity map at 100 cfs (left), 500 cfs (center), and 1,000 cfs (right). Velocity for all depths is shown at 100 cfs. Velocity classification is only shown for depths greater than 1 ft at 500 cfs and 1,000 cfs.

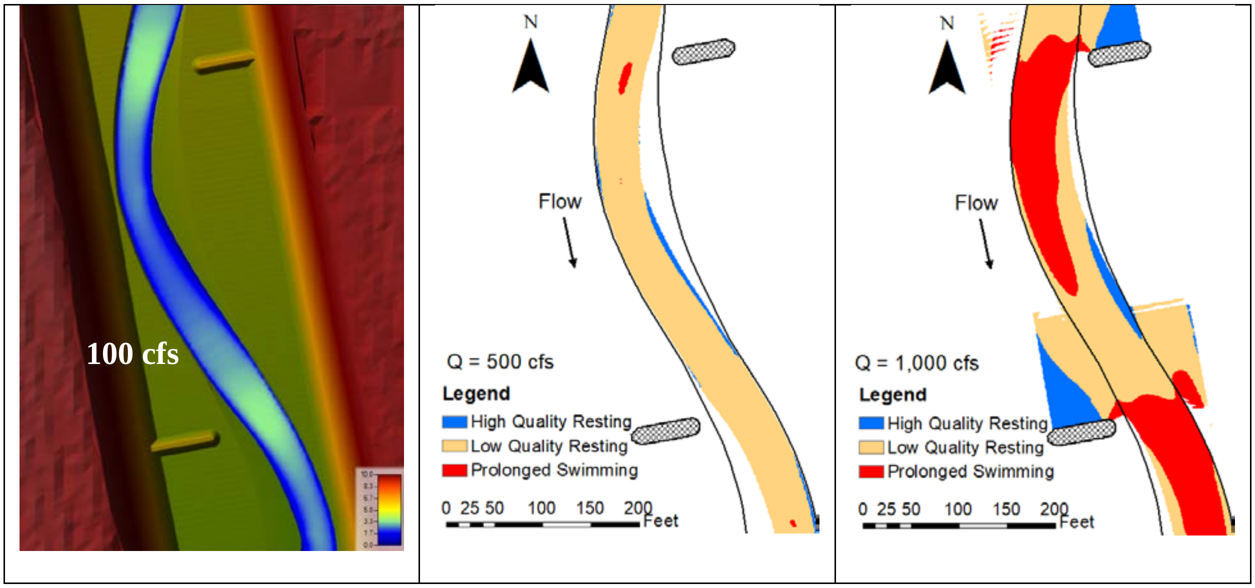

Figure A 9. Deflectors outside LFC (G9) velocity map at 100 cfs (left), 500 cfs (center), and 1,000 cfs (right). Velocity for all depths is shown at 100 cfs. Velocity classification is only shown for depths greater than 1 ft at 500 cfs and 1,000 cfs.

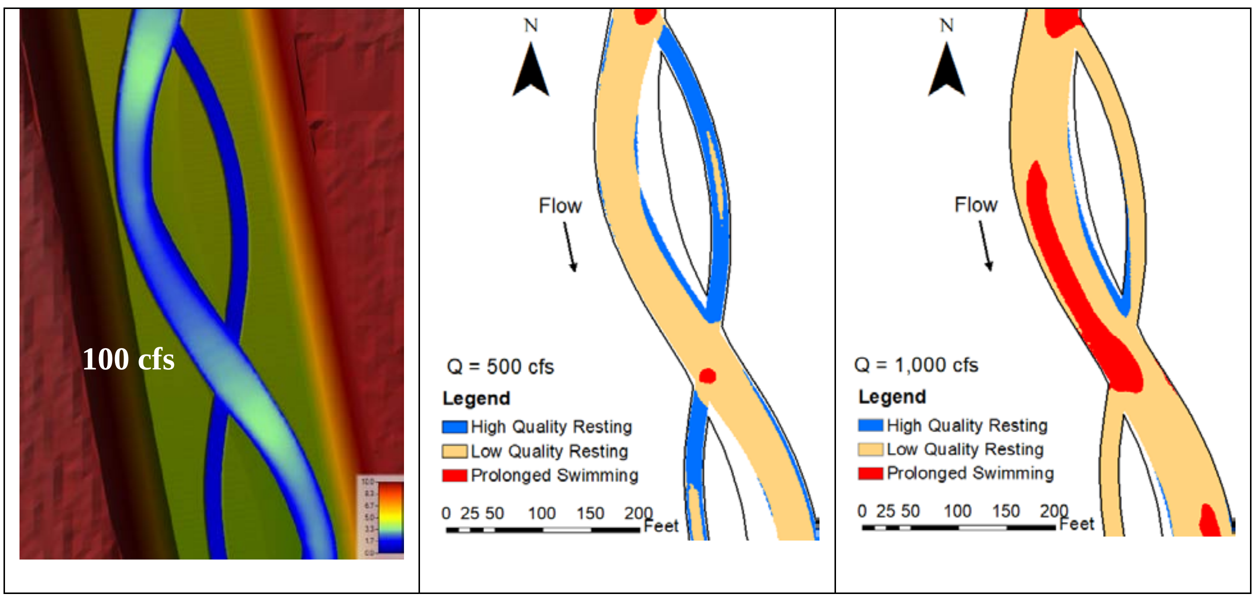

Figure A 10. Multi-threaded LFC (G10) velocity map at 100 cfs (left), 500 cfs (center), and 1,000 cfs (right). Velocity for all depths is shown at 100 cfs. Velocity classification is only shown for depths greater than 1 ft at 500 cfs and 1,000 cfs.

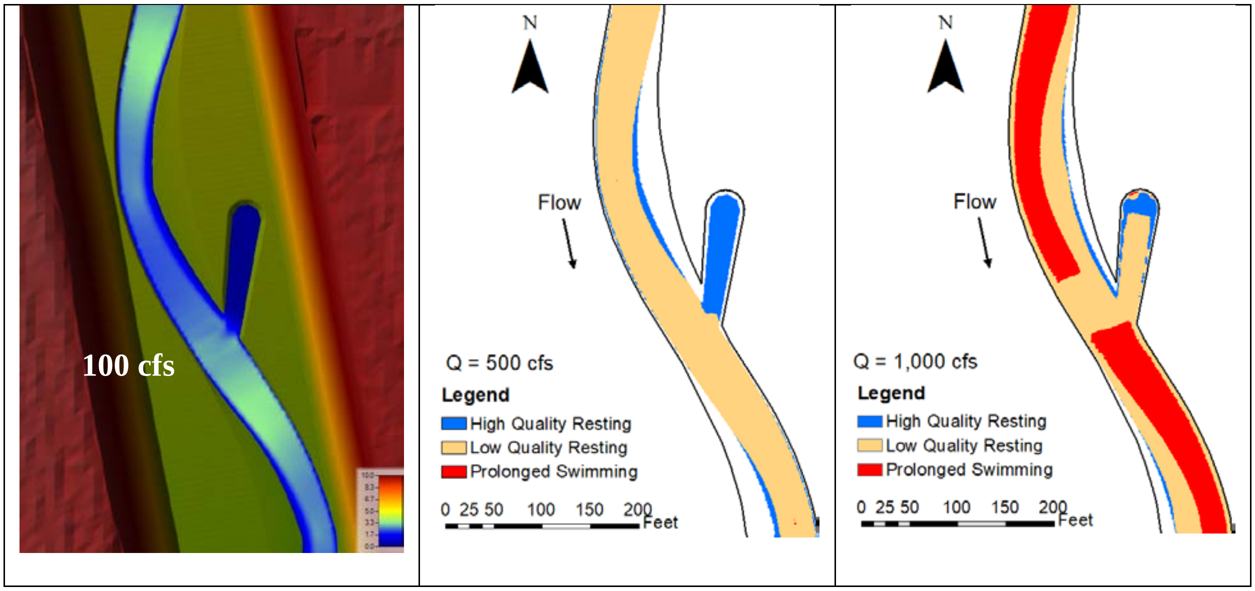

Figure A 11. Backwaters (G11) velocity map at 100 cfs (left), 500 cfs (center), and 1,000 cfs (right). Velocity for all depths is shown at 100 cfs. Velocity classification is only shown for depths greater than 1 ft at 500 cfs and 1,000 cfs.

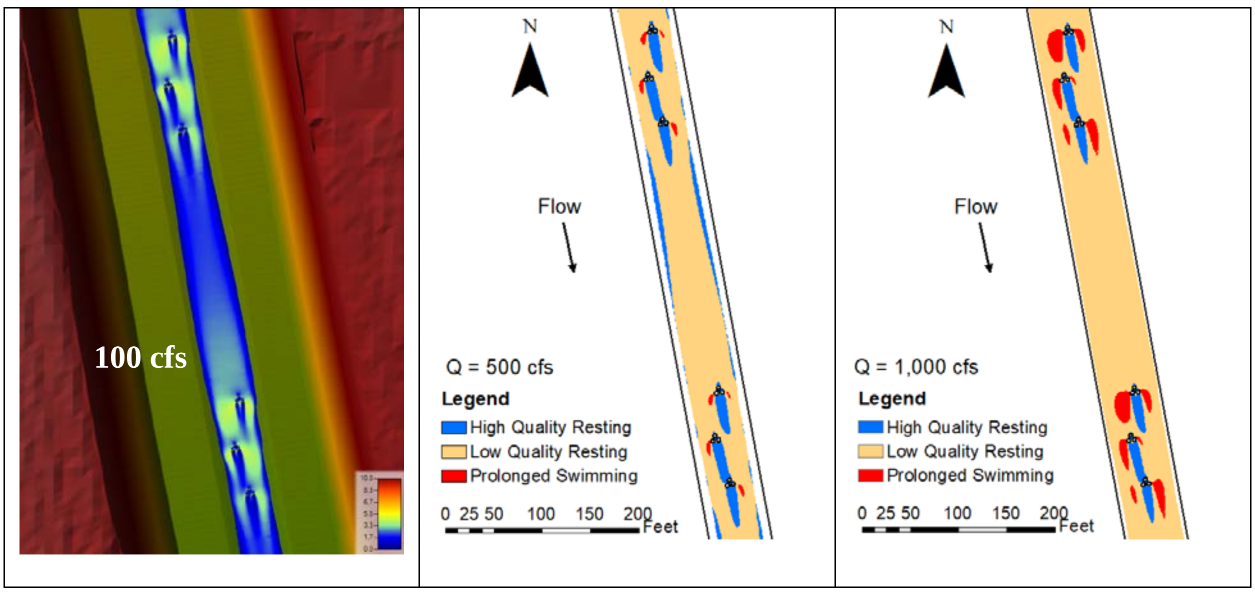

Figure A 12. Boulder clusters within LFC (G12) velocity map at 100 cfs (left), 500 cfs (center), and 1,000 cfs (right). Velocity for all depths is shown at 100 cfs. Velocity classification is only shown for depths greater than 1 ft at 500 cfs and 1,000 cfs.

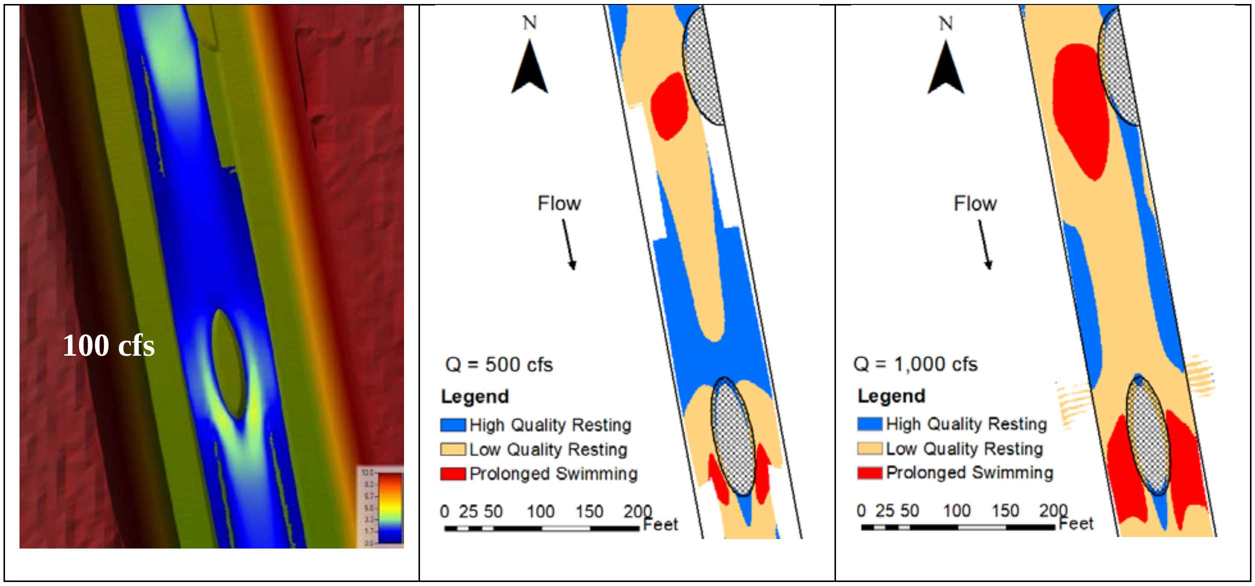

Figure A 13. Mid-channel islands and alternating bars within LFC (G13) velocity map at 100 cfs (left), 500 cfs (center), and 1,000 cfs (right). Velocity for all depths is shown at 100 cfs. Velocity classification is only shown for depths greater than 1 ft at 500 cfs and 1,000 cfs.

Appendix B – Test Matrix and Rock Dimensions

Table B 1. Test matrix of prototype flows, boulder configuration, density of rock configurations, and number of boulders showing the associated percent of suitable area based on high-quality resting habitat (0-3 ft/s) for adult Steelhead. The density of rock configurations refers to the number of rock clusters in the model for the test, where high has the most clusters and low has the lowest amount of clusters.

Test No.	Configuration	Density	Flow Rate	No. Boulders	Unsuitable Resting (>5fps)	Low Quality Resting (3-5fps)	High Quality Resting (<3fps)	Total Pts	% High Quality
a	Baseline	n/a	300	0	1429	1012	738	3179	23.21
b	Baseline	n/a	600	0	2320	718	651	3689	17.65
1	Single	Medium	300	4	144	1367	958	2469	38.80
2	Single	Medium	600	4	851	1477	196	2524	7.77
3	Single	Med-High	300	6	129	1239	1332	2700	49.33
4	Single	Med-High	600	6	753	1609	526	2888	18.21
5	Single	High	300	8	221	1679	1371	3271	41.91
6	Single	High	600	8	1380	1901	751	4032	18.63
7	Single	Low	300	2	1525	1002	690	3217	21.45
8	Single	Low	600	2	1703	581	80	2364	3.38
9	Upstream "V"	High	300	12	4	900	2549	3453	73.82
10	Upstream "V"	High	600	12	403	1666	1493	3562	41.91
11	Upstream "V"	Medium	300	9	143	1181	1800	3124	57.62
12	Upstream "V"	Medium	600	9	556	1528	1602	3686	43.46
13	Upstream "V"	Low	300	6	641	849	1887	3377	55.88
14	Upstream "V"	Low	600	6	1118	1019	1204	3341	36.04
15	Downstream "V"	High	300	12	77	1279	2318	3674	63.09
16	Downstream "V"	High	600	12	474	2611	1246	4331	28.77
17	Downstream "V"	Medium	300	9	79	1145	2507	3731	67.19
18	Downstream "V"	Medium	600	9	737	1692	1422	3851	36.93
19	Downstream "V"	Low	300	6	557	894	1599	3050	52.43
20	Downstream "V"	Low	600	6	1199	1494	968	3661	26.44
21	Diamond	High	300	16	23	1035	2659	3717	71.54

22	Diamond	High	600	16	231	1643	1255	3129	40.11
23	Diamond	Medium	300	12	107	1123	2172	3402	63.84
24	Diamond	Medium	600	12	575	1647	1431	3653	39.17
25	Diamond	Low	300	8	524	996	1949	3469	56.18
26	Diamond	Low	600	8	979	1340	1264	3583	35.28

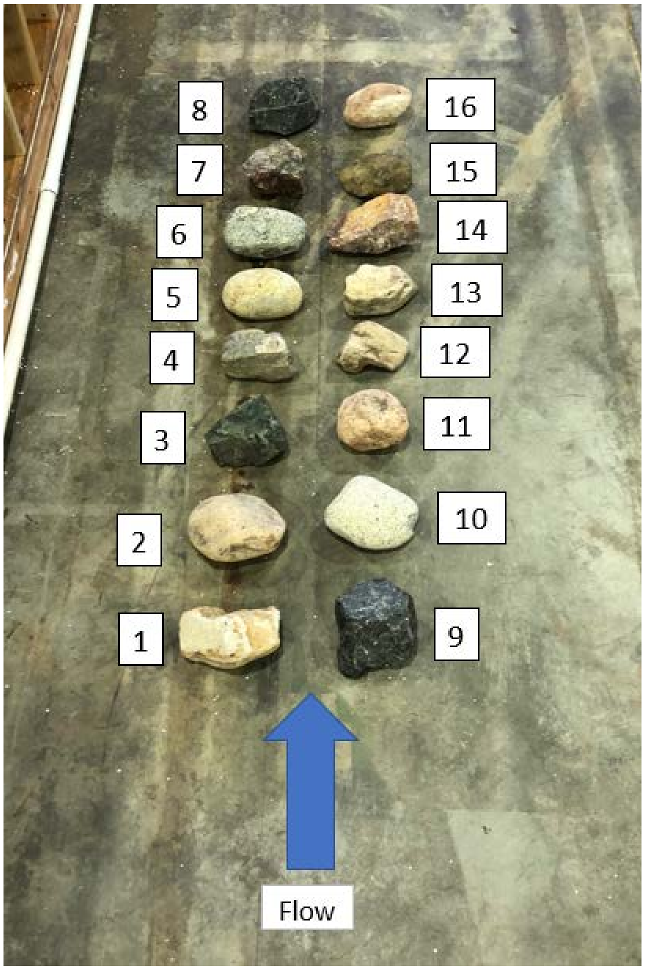

Figure B 1. Image of boulders used during testing with associated numbers for tracking

Table B 2. Cluster number with corresponding boulders utilized in each configuration.

Clusters	Boulders Used (Diamond)	Boulders Used (Both V Configurations)
1	1, 8, 9, 10	1, 8, 9
2	2, 11, 12, 13	2, 11, 12
3	3, 7, 5, 14	3, 7, 5
4	4, 6, 15, 16	4, 6, 15

Table B 3: Rock number with corresponding dimensions in feet. For this study: “x” corresponds to the horizontal length of rock obstructing the flow, “y” is the vertical height of the rock, and “z” is the depth of the rock into the flow taken at the middle point of the rock.

Rock Number	Dimension in feet		
	x	y	z
1	1.02	0.65	0.65
2	1.06	0.60	0.78
3	0.97	0.75	0.77
4	0.94	0.56	0.63
5	1.04	0.65	0.73
6	1.06	0.66	0.71
7	0.83	0.61	0.96
8	1.02	0.63	0.79
9	0.85	0.63	0.89
10	1.09	0.53	0.85
11	0.83	0.63	0.69
12	0.92	0.58	0.46
13	0.98	0.58	0.63
14	1.31	0.65	0.70
15	1.02	0.56	0.50
16	1.00	0.60	0.54

Appendix C – Hydraulic Modeling Results from PIVLab and TecPlot Focus

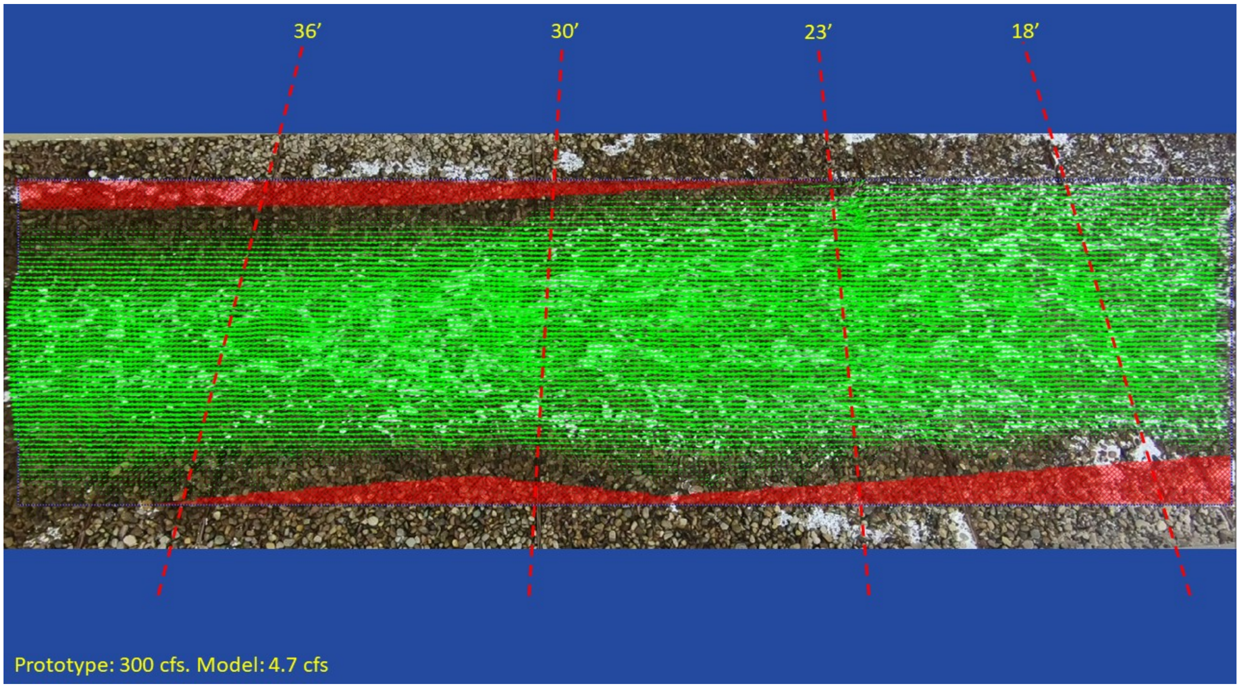

Figure C 1. PIVLab output of velocity vectors at 300 cfs baseline flow through the channel. Baseline ADV measurement transects are indicated with dotted lines. Distances marked in figure represent offset downstream from the model headbox. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

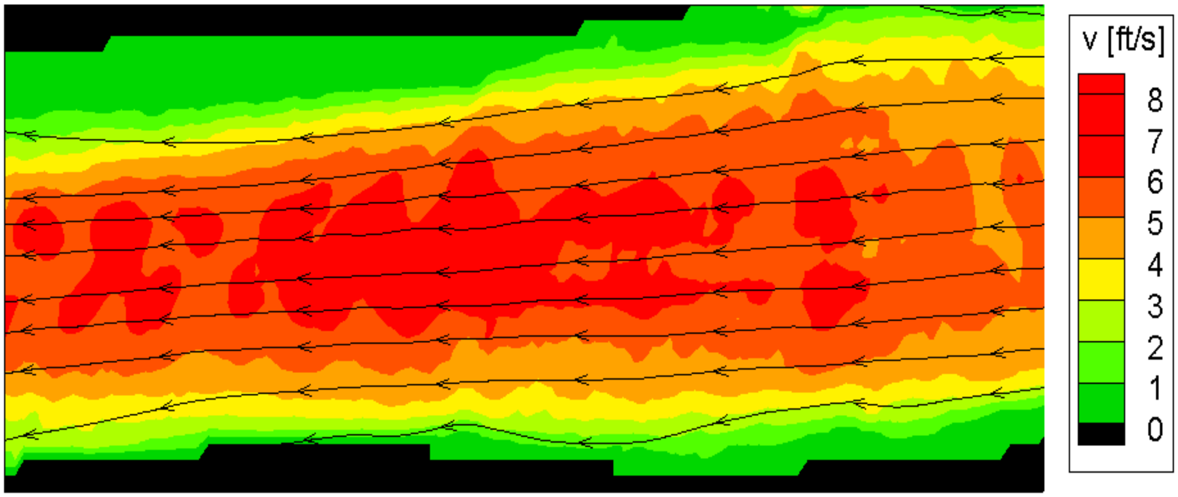

Figure C 2. TecPlot output for velocity at 300 cfs baseline flow through the channel. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

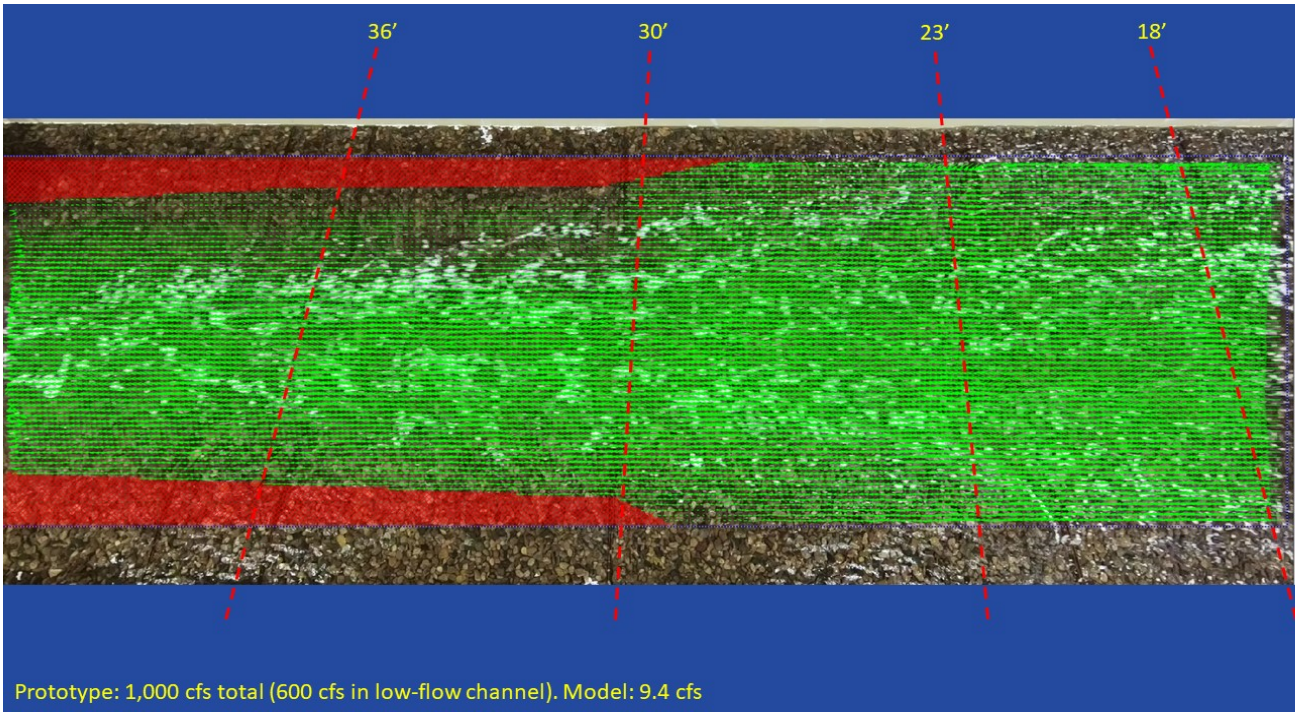

Figure C 3. PIVLab output of velocity vectors at 600 cfs baseline flow through the channel. Baseline ADV measurement transects are indicated with dotted lines. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

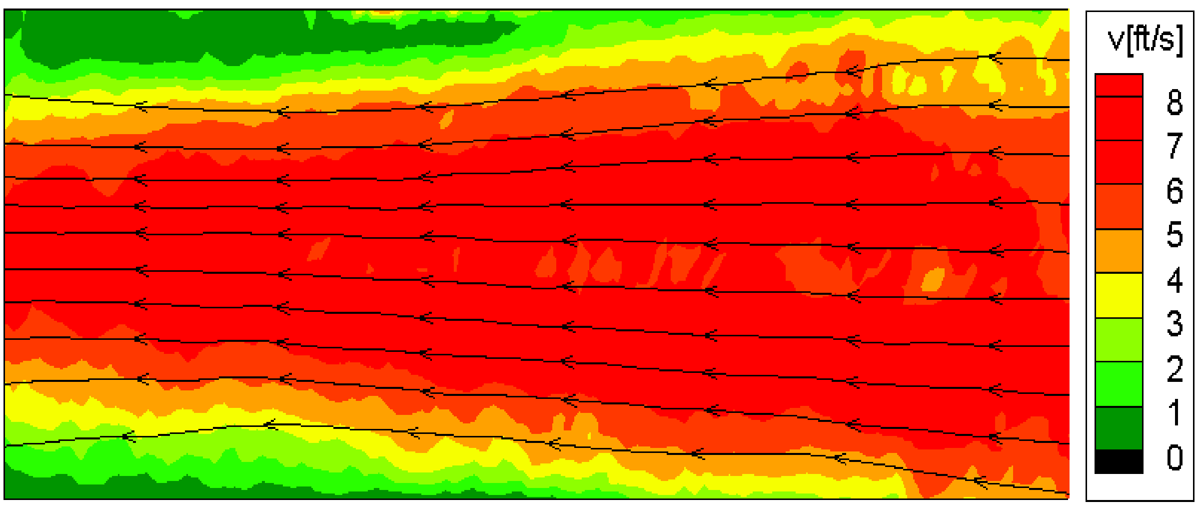

Figure C 4. TecPlot output for 600 cfs baseline flow through the channel. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

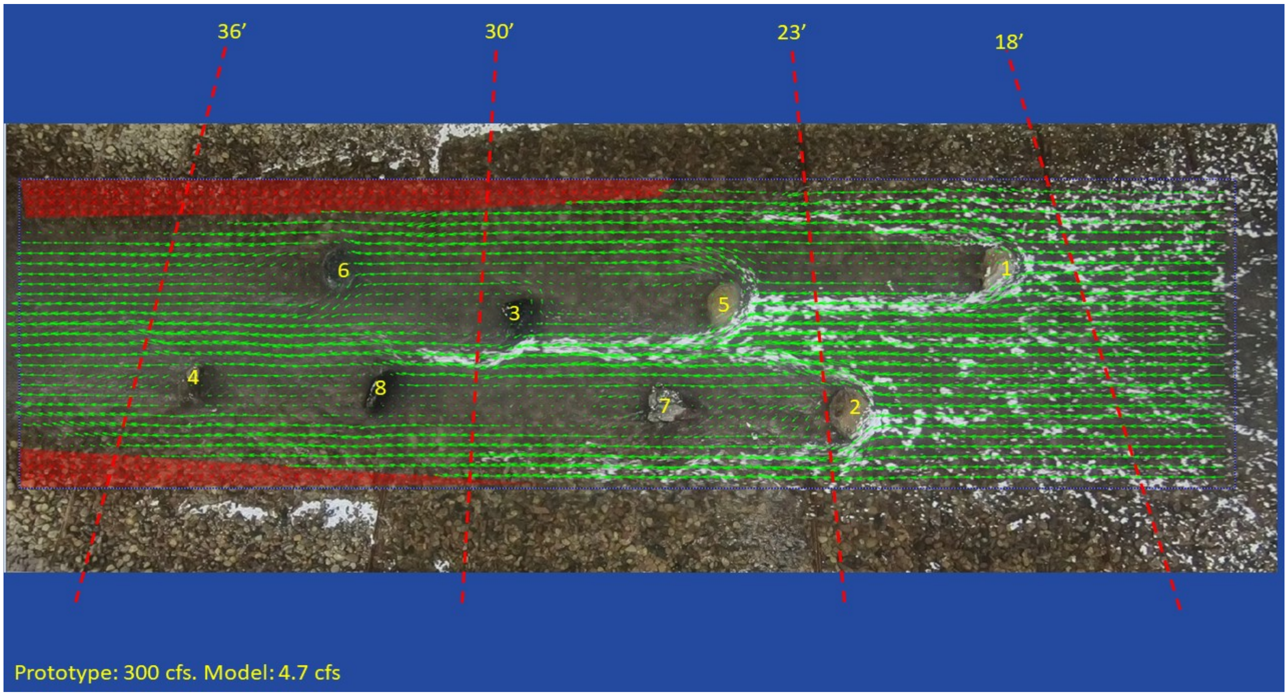

Figure C 5. PIVLab output of velocity vectors at 300 cfs for the single rock, high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

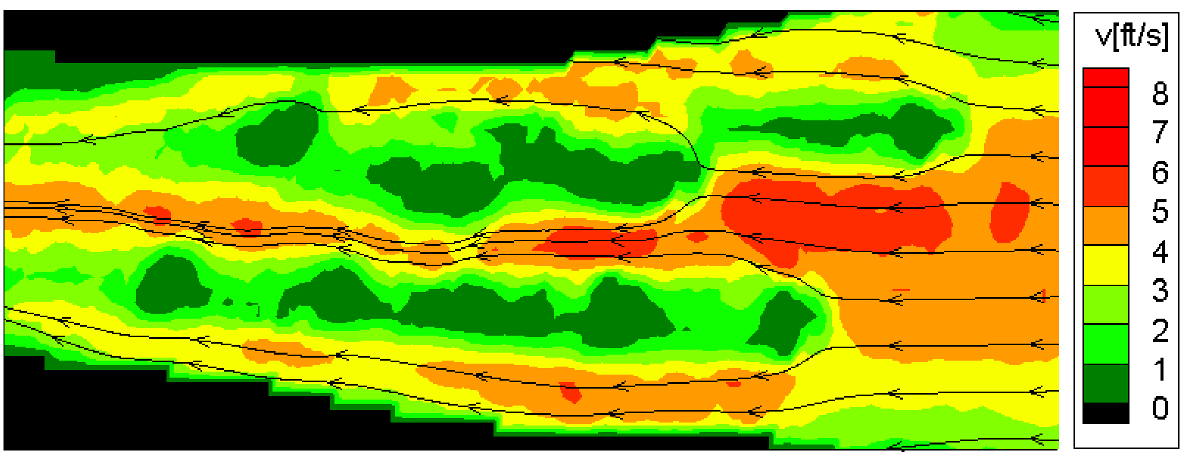

Figure C 6. TecPlot output for velocity at 300 cfs at the single rock, high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

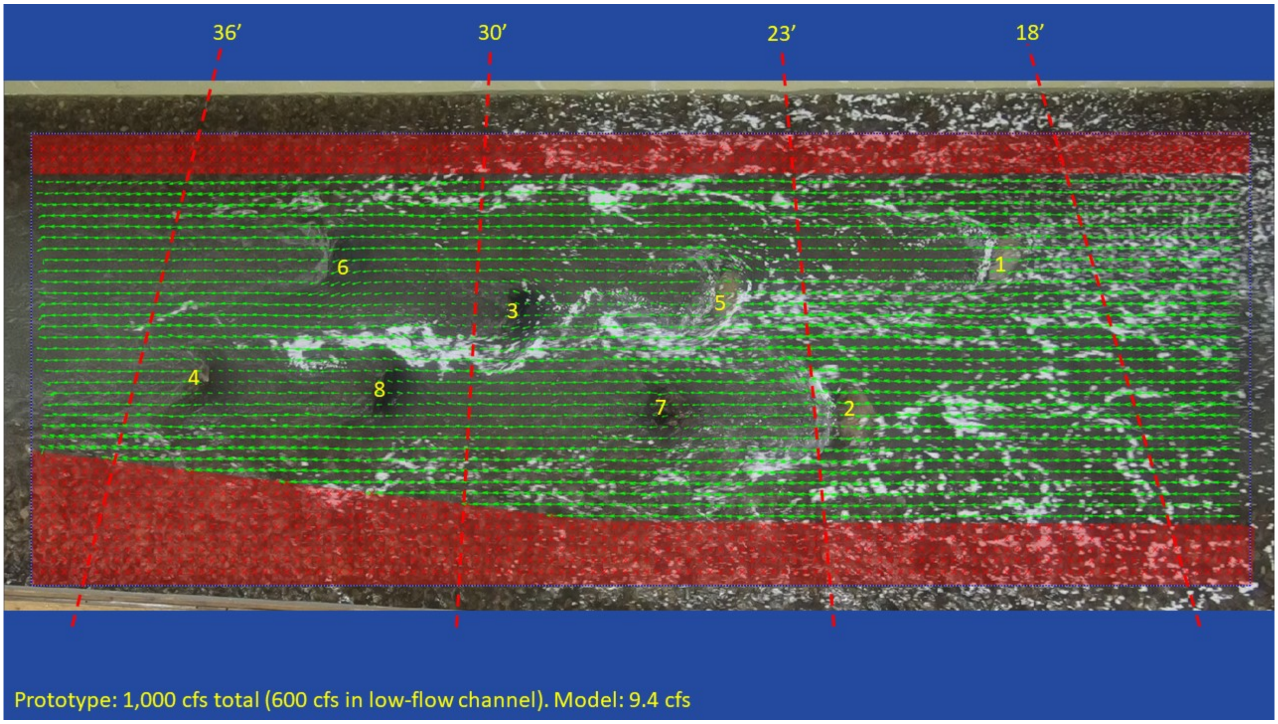

Figure C 7. PIVLab output of velocity vectors at 600 cfs at the single rock, high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

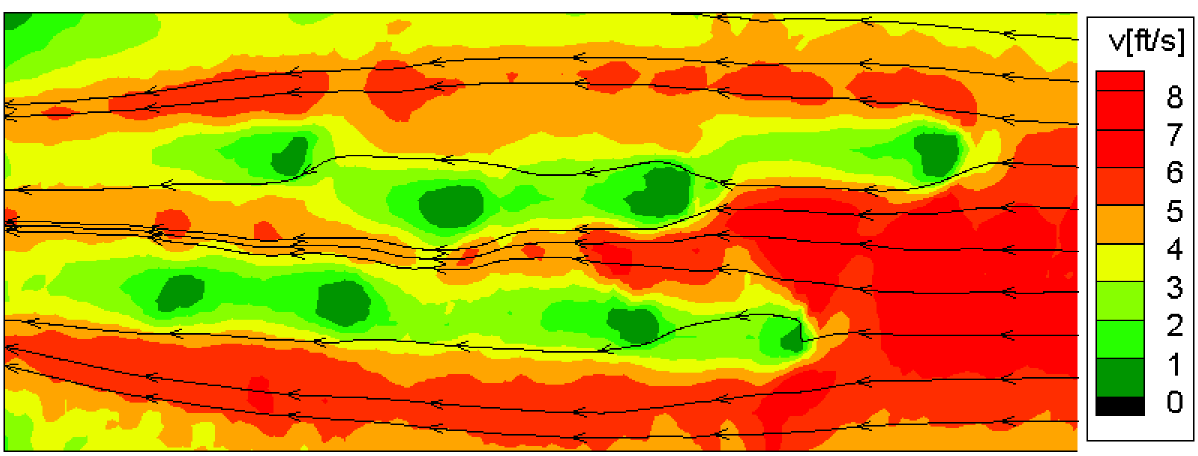

Figure C 8. TecPlot output for velocity at 600 cfs at the single rock, high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

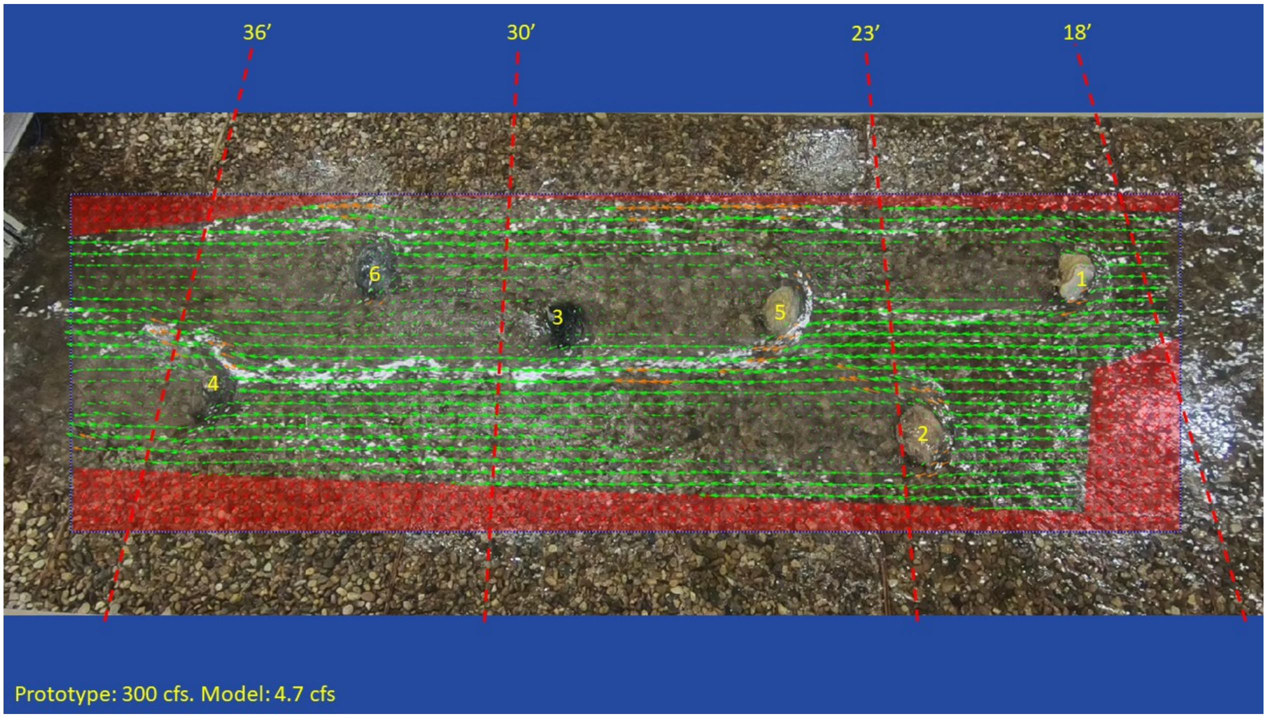

Figure C 9. PIVLab output of velocity vectors at 300 cfs at the single rock, medium high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

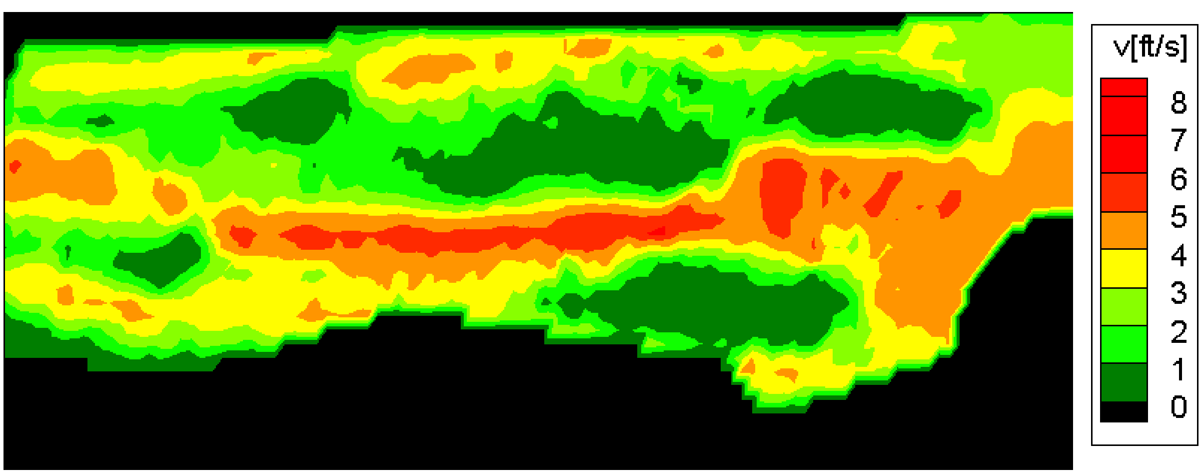

Figure C 10. TecPlot output for velocity at 300 cfs at the single rock, medium high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

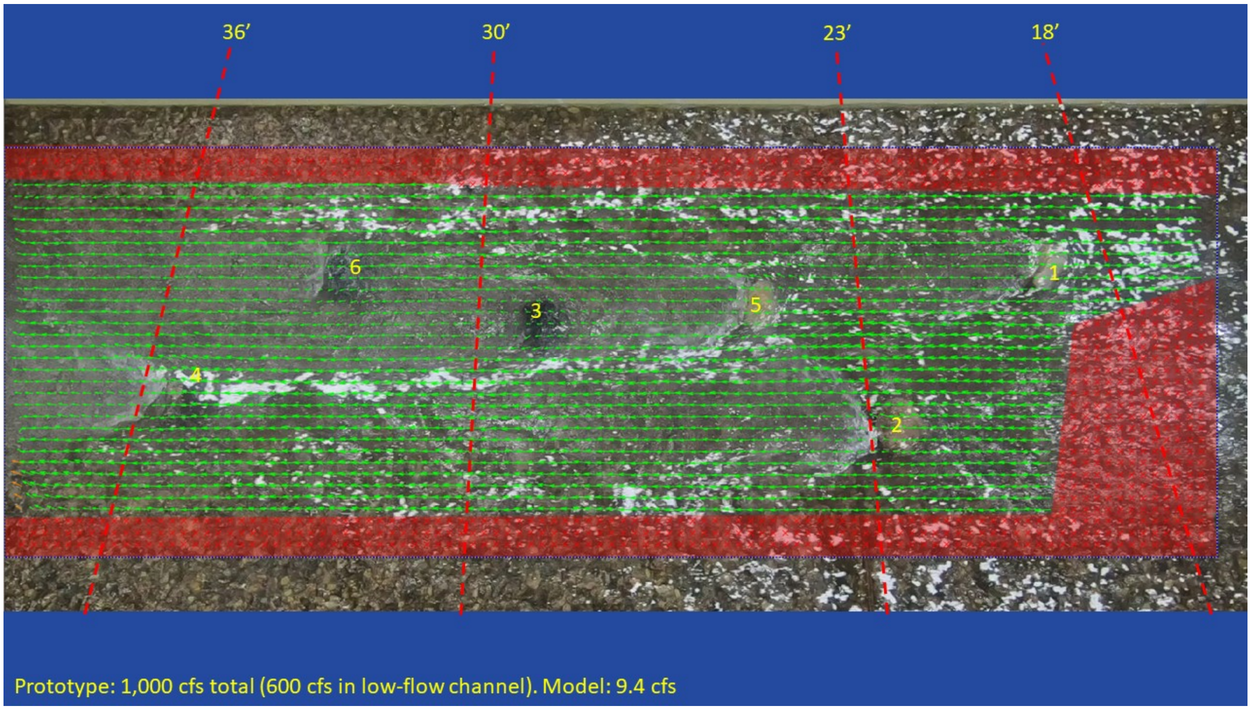

Figure C 11. PIVLab output of velocity vectors at 600 cfs at the single rock, medium high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

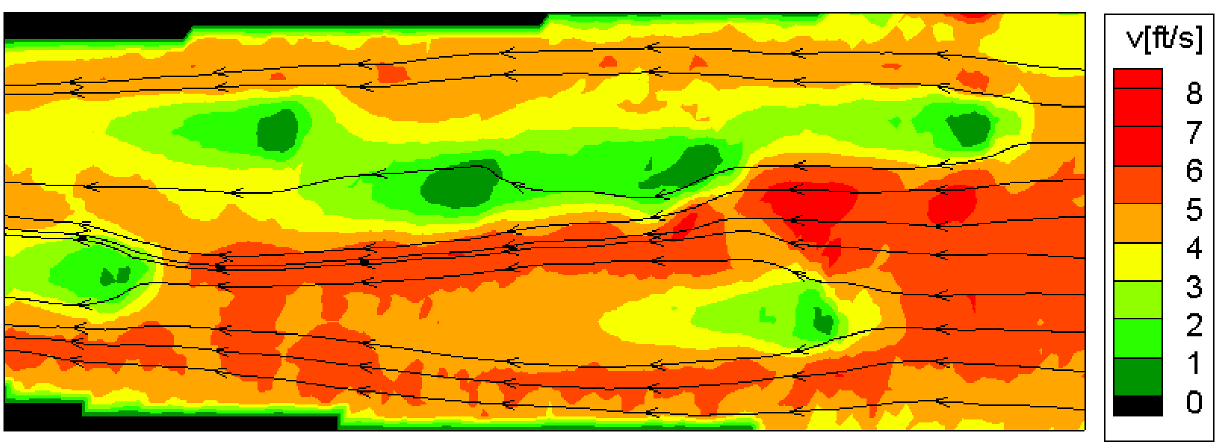

Figure C 12. TecPlot output for velocity at 600 cfs at the single rock, medium high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

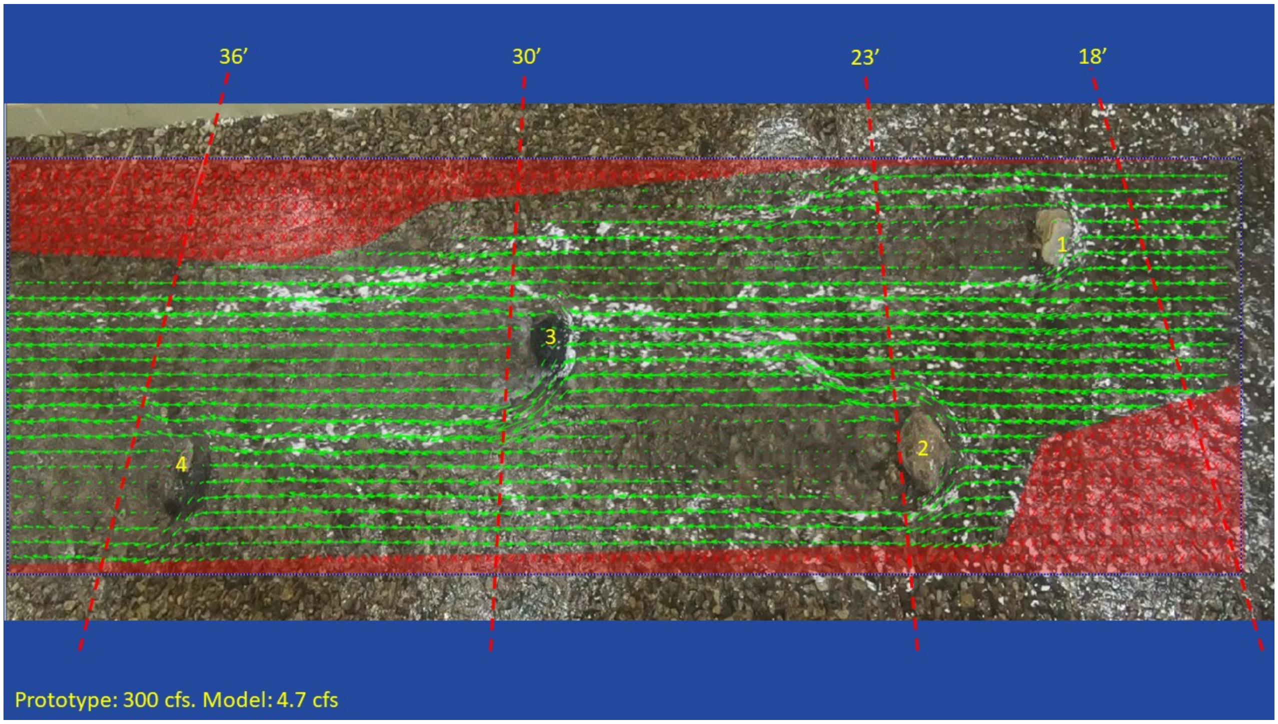

Figure C 13. PIVLab output of velocity vectors at 300 cfs at the single rock, medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

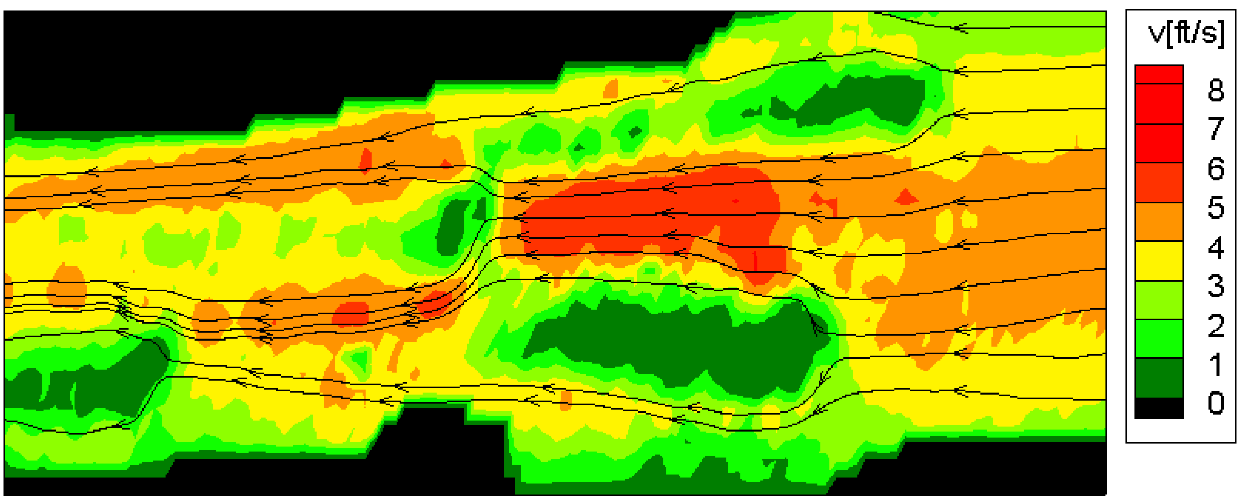

Figure C 14. TecPlot output for velocity at 300 cfs at the single rock, medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

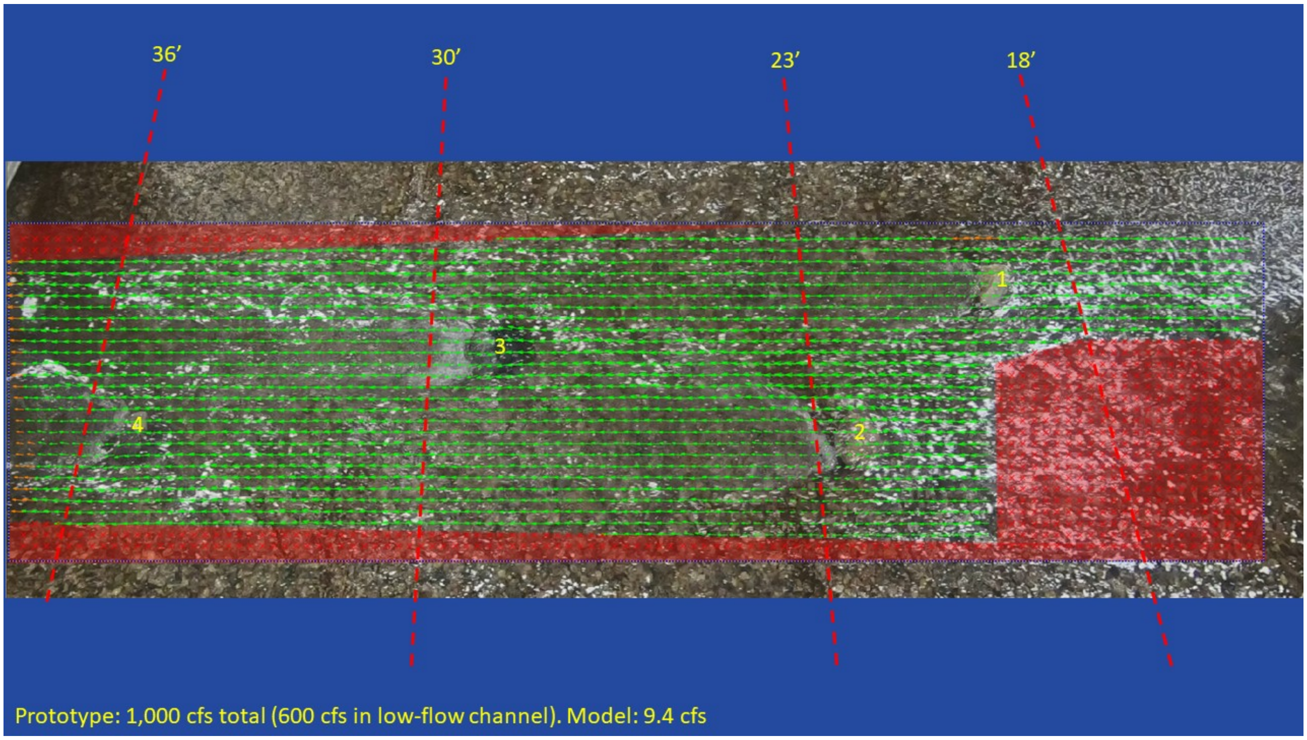

Figure C 15. PIVLab output of velocity vectors at 600 cfs at the single rock, medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

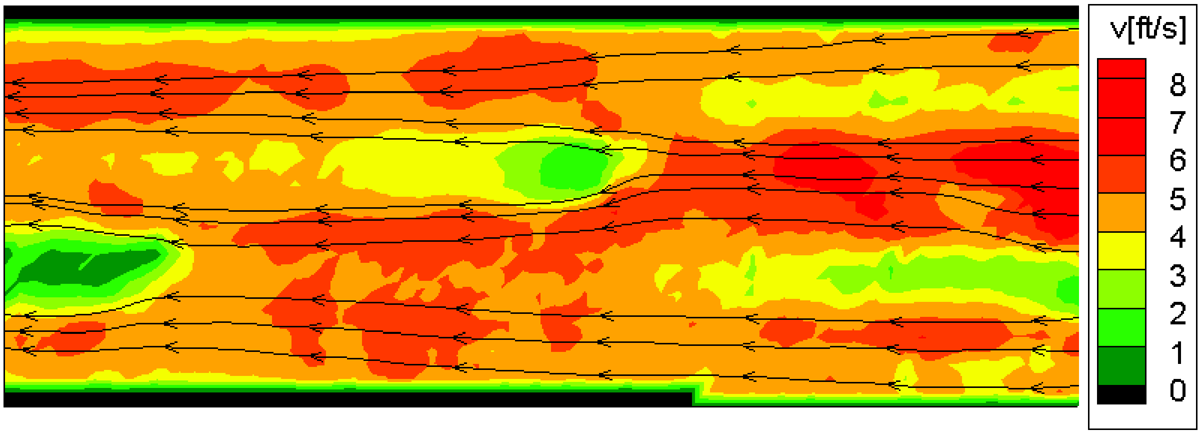

Figure C 16. TecPlot output for velocity at 600 cfs at the single rock, medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

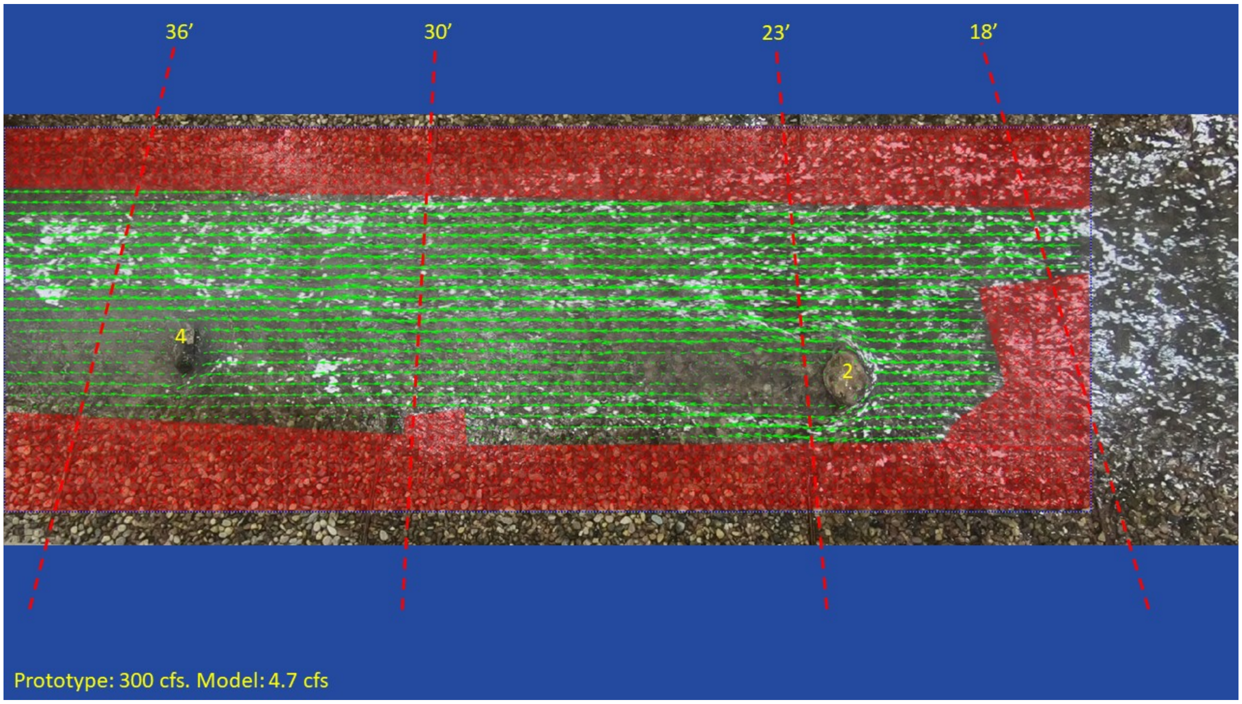

Figure C 17. PIVLab output of velocity vectors at 300 cfs at the single rock, low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

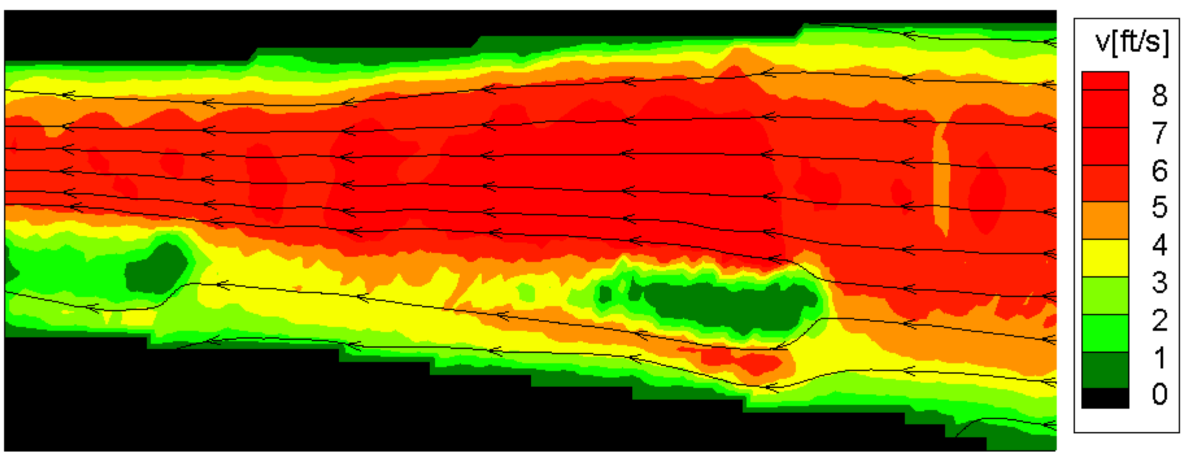

Figure C 18. TecPlot output for velocity at 300 cfs at the single rock, low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

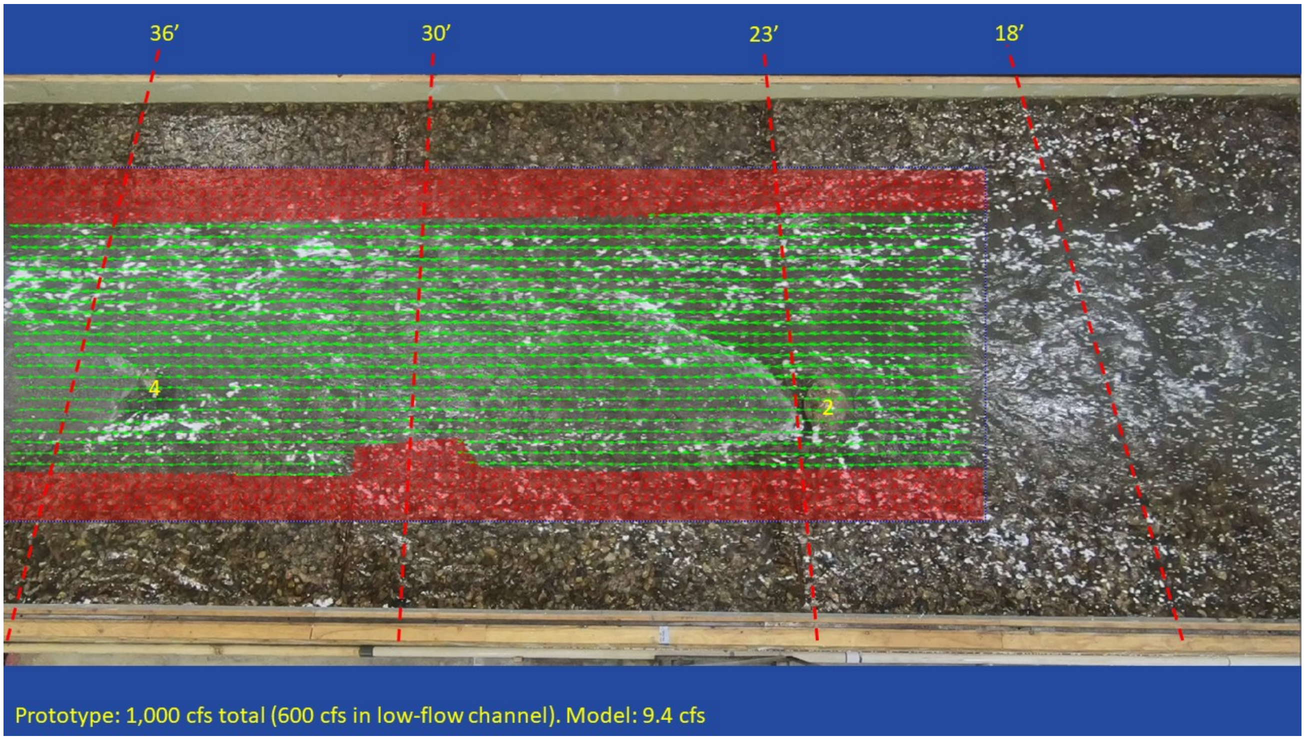

Figure C 19. PIVLab output of velocity vectors at 600 cfs at the single rock, low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

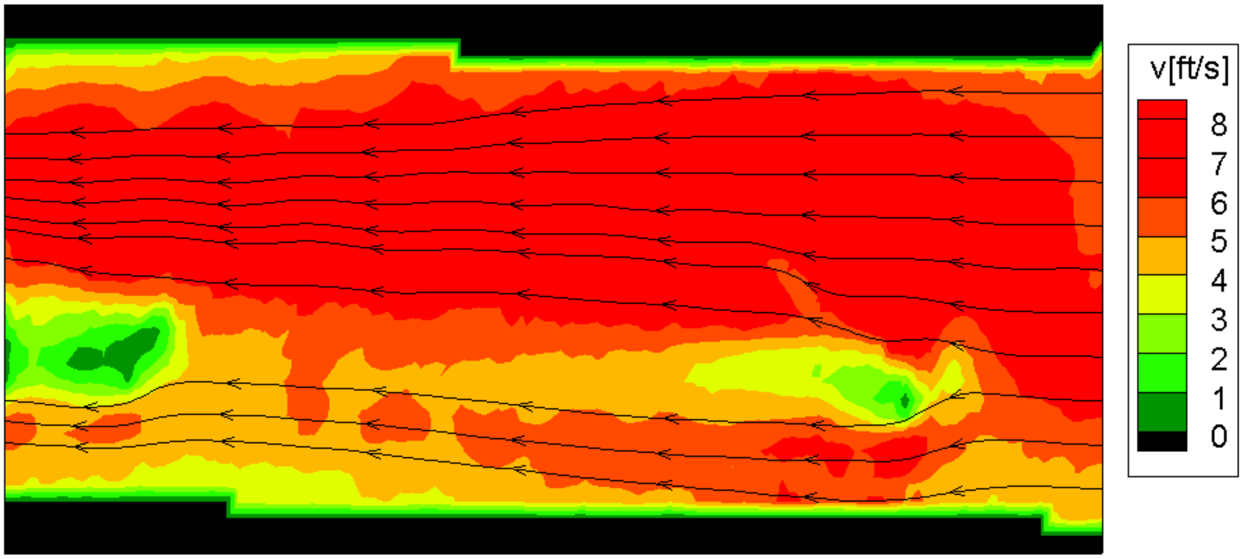

Figure C 20. TecPlot output for velocity at 600 cfs at the single rock, low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

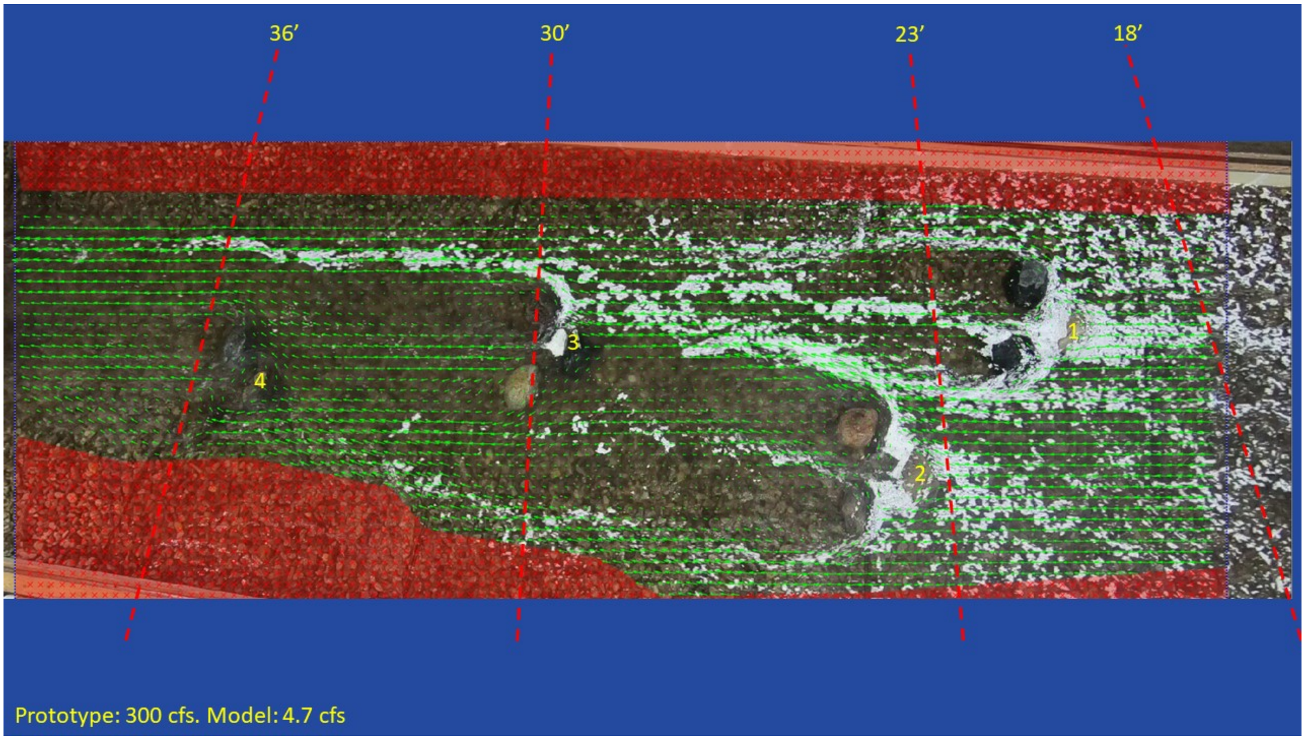

Figure C 21. PIVLab output of velocity vectors at 300 cfs at the upstream "V", high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

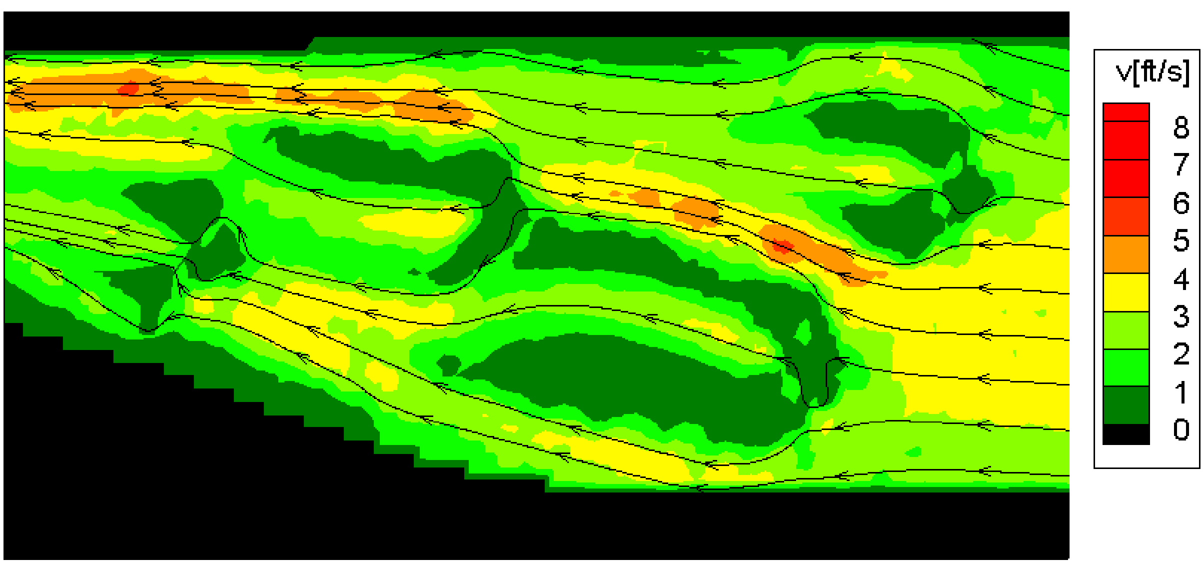

Figure C 22. TecPlot output for velocity at 300 cfs at the upstream "V", high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

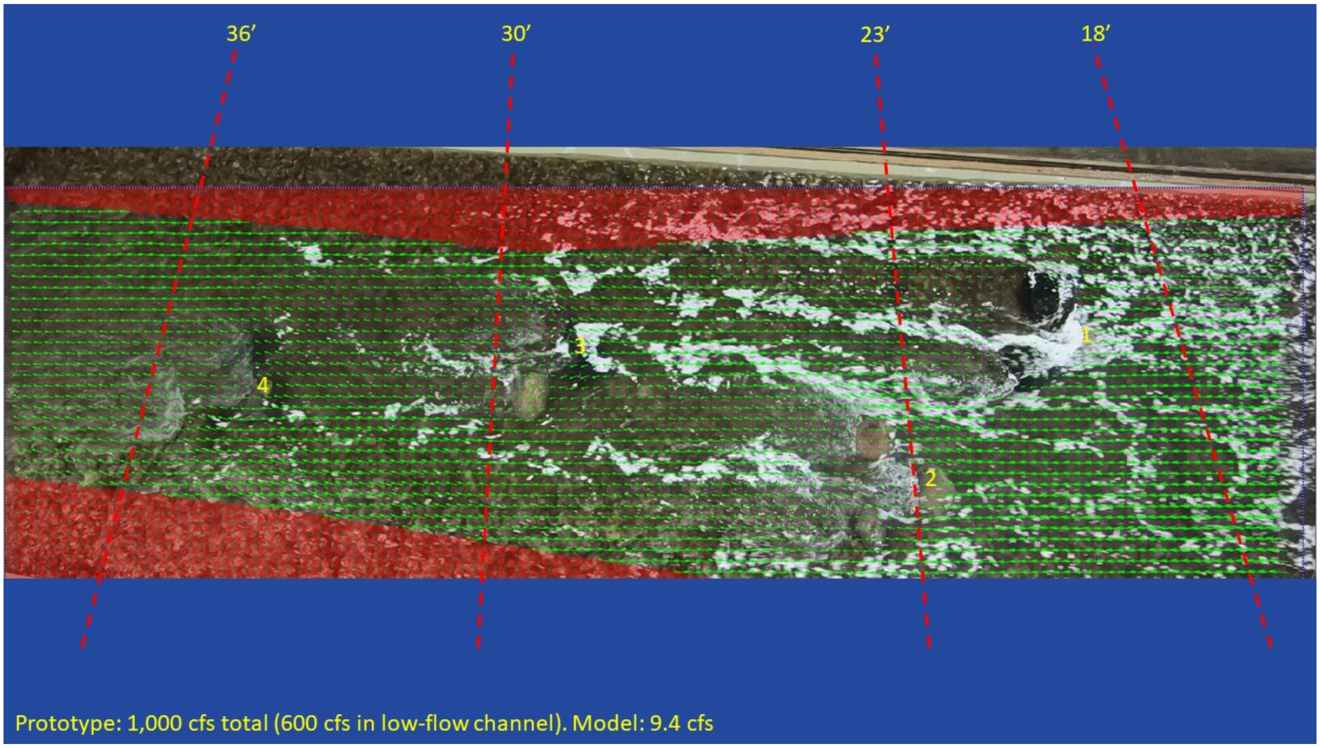

Figure C 23. PIVLab output of velocity vectors at 600 cfs at the upstream "V", high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

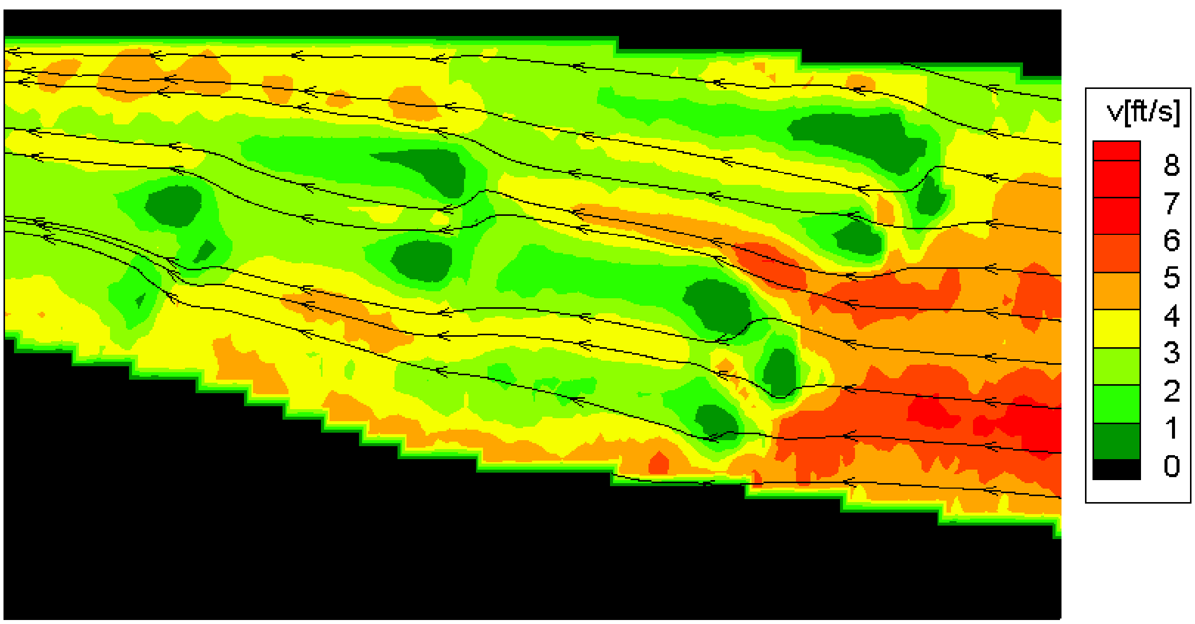

Figure C 24. TecPlot output for velocity at 600 cfs at the upstream "V", high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

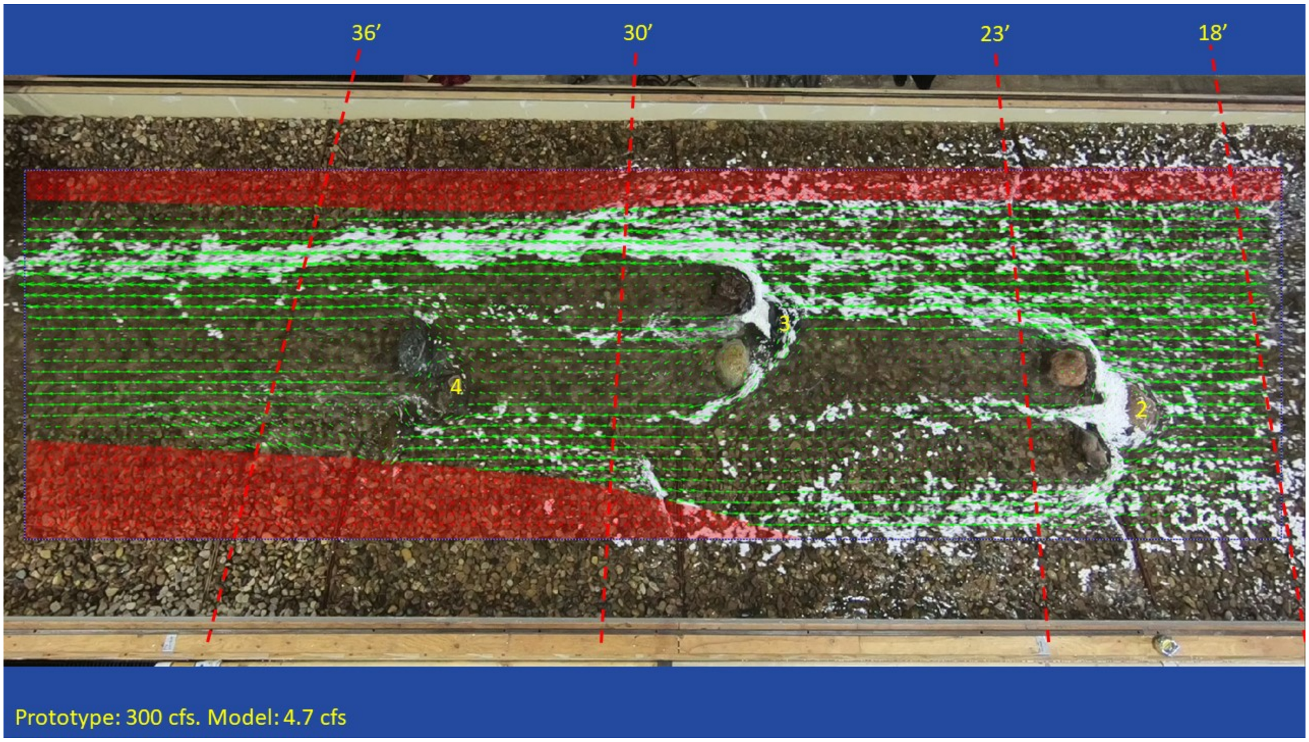

Figure C 25. PIVLab output of velocity vectors at 300 cfs at the upstream "V", medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

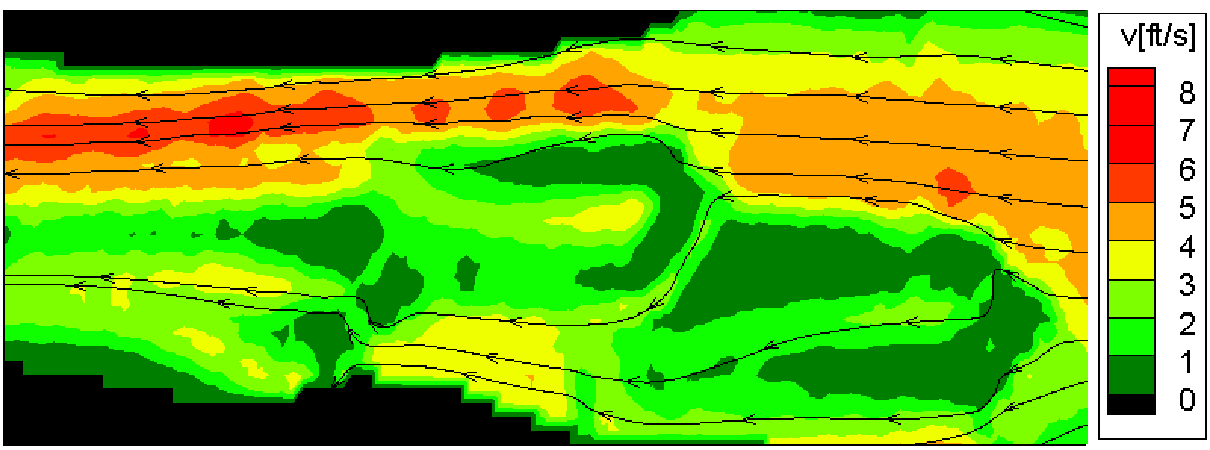

Figure C 26. TecPlot output for velocity at 300 cfs at the upstream "V", medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

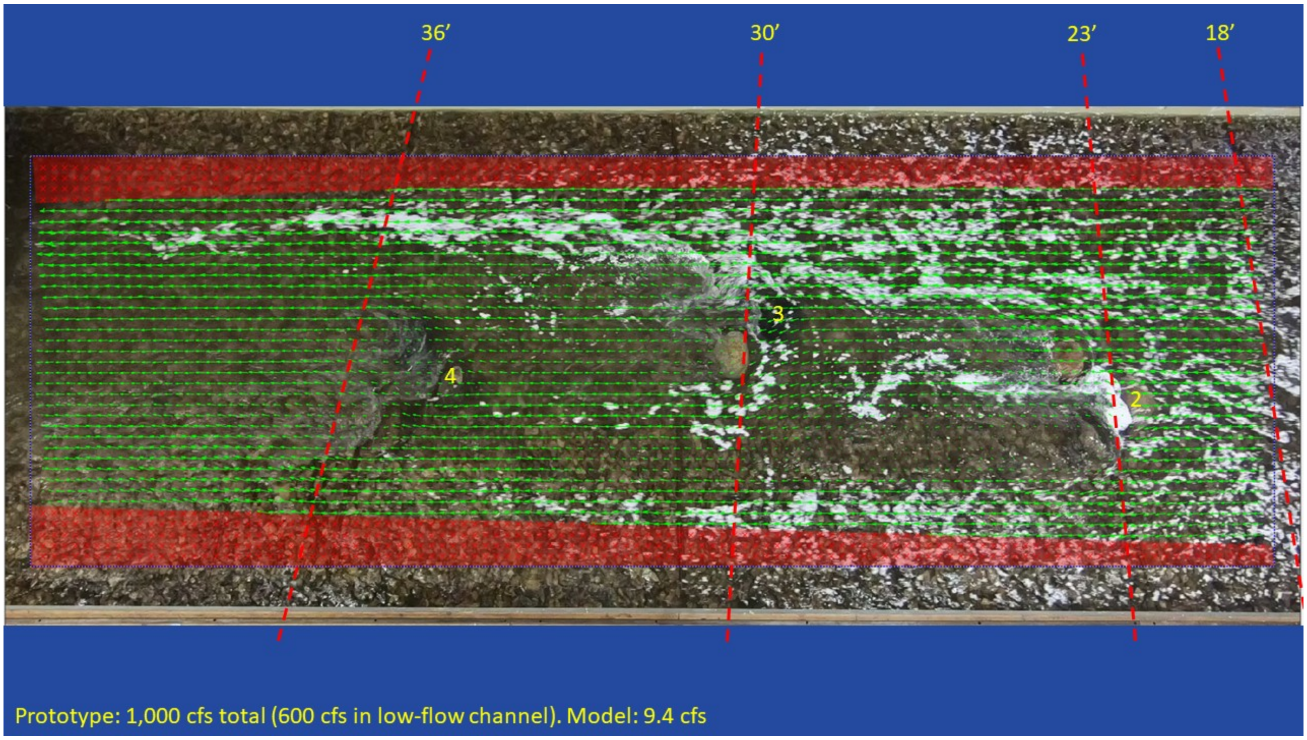

Figure C 27. PIVLab output of velocity vectors at 600 cfs at the upstream "V", medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

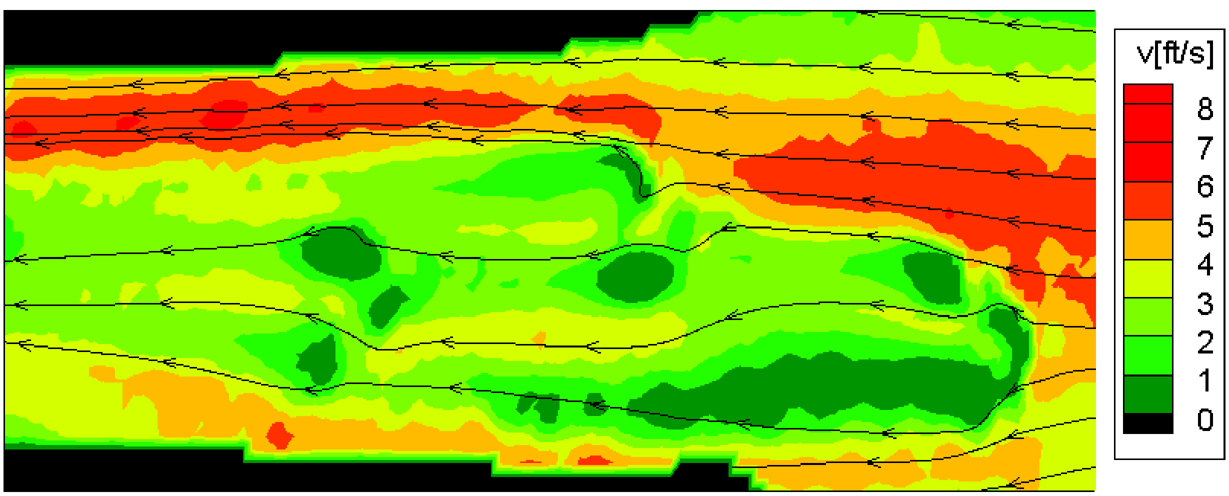

Figure C 28. TecPlot output for velocity at 600 cfs at the upstream "V", medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

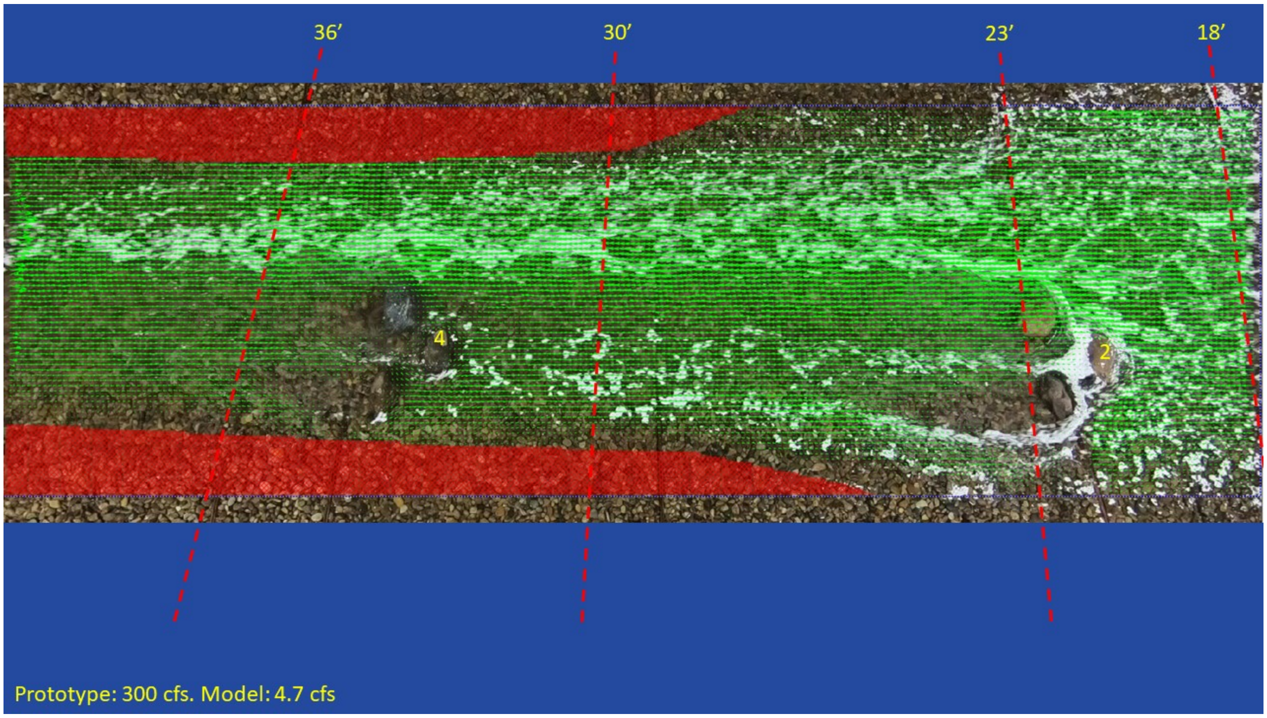

Figure C 29. PIVLab output of velocity vectors at 300 cfs at the upstream "V", low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

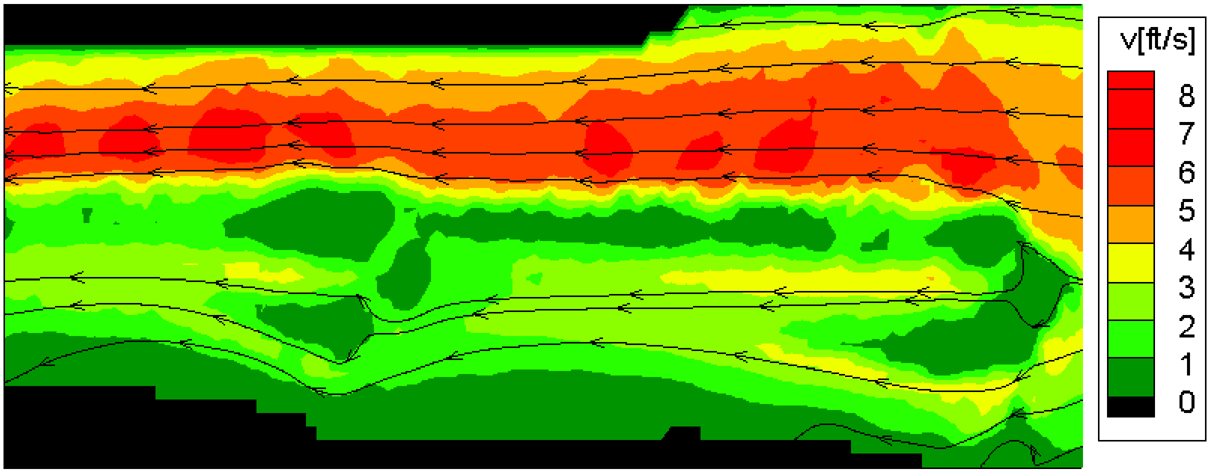

Figure C 30. TecPlot output for velocity at 300 cfs at the upstream "V", low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

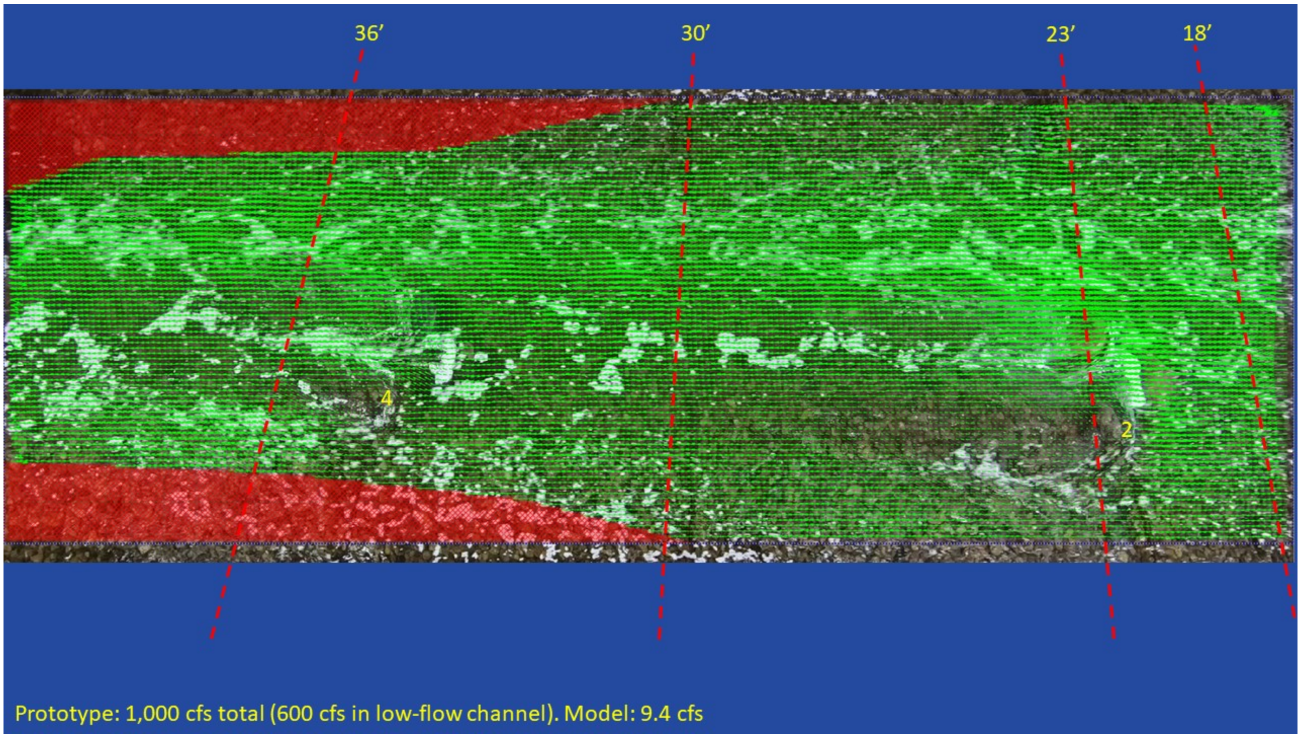

Figure C 31. PIVLab output of velocity vectors at 600 cfs at the upstream "V", low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

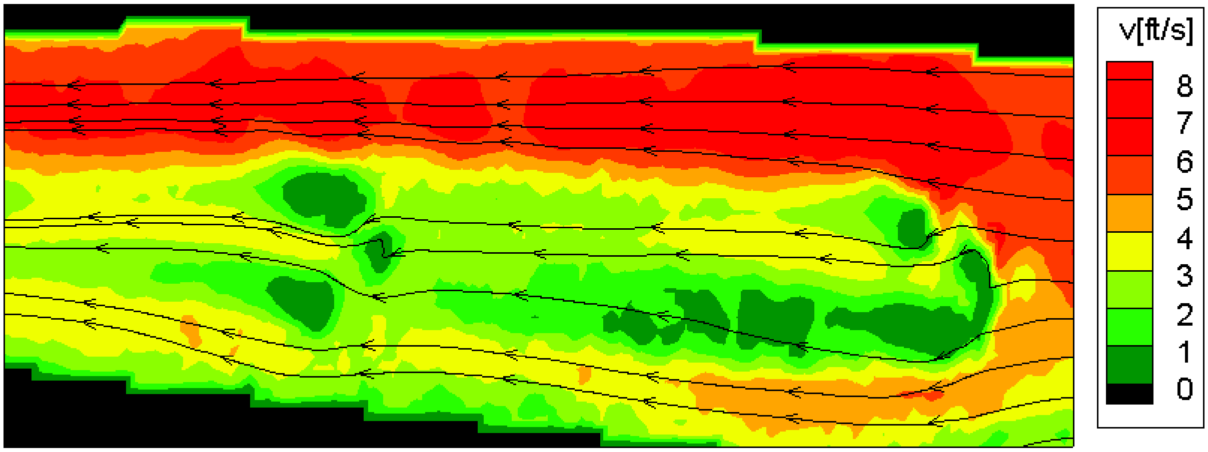

Figure C 32. TecPlot output for velocity at 600 cfs at the upstream "V", low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

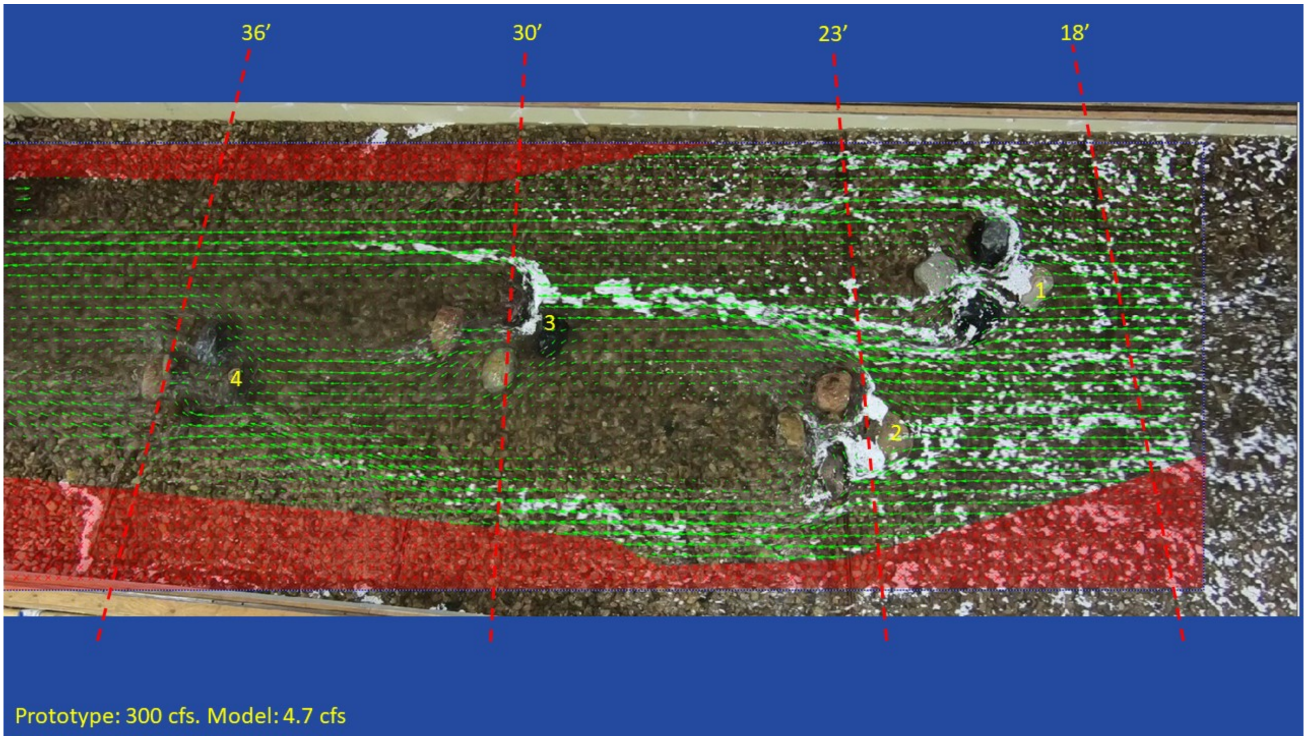

Figure C 33. PIVLab output of velocity vectors at 300 cfs at the diamond, high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

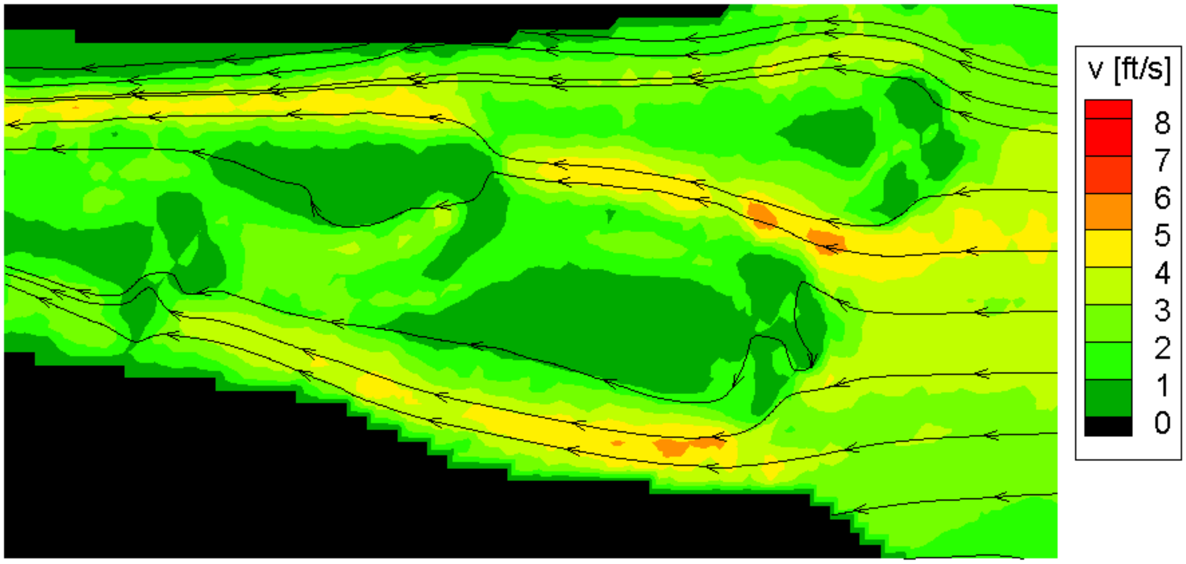

Figure C 34. TecPlot output for velocity at 300 cfs at the diamond, high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

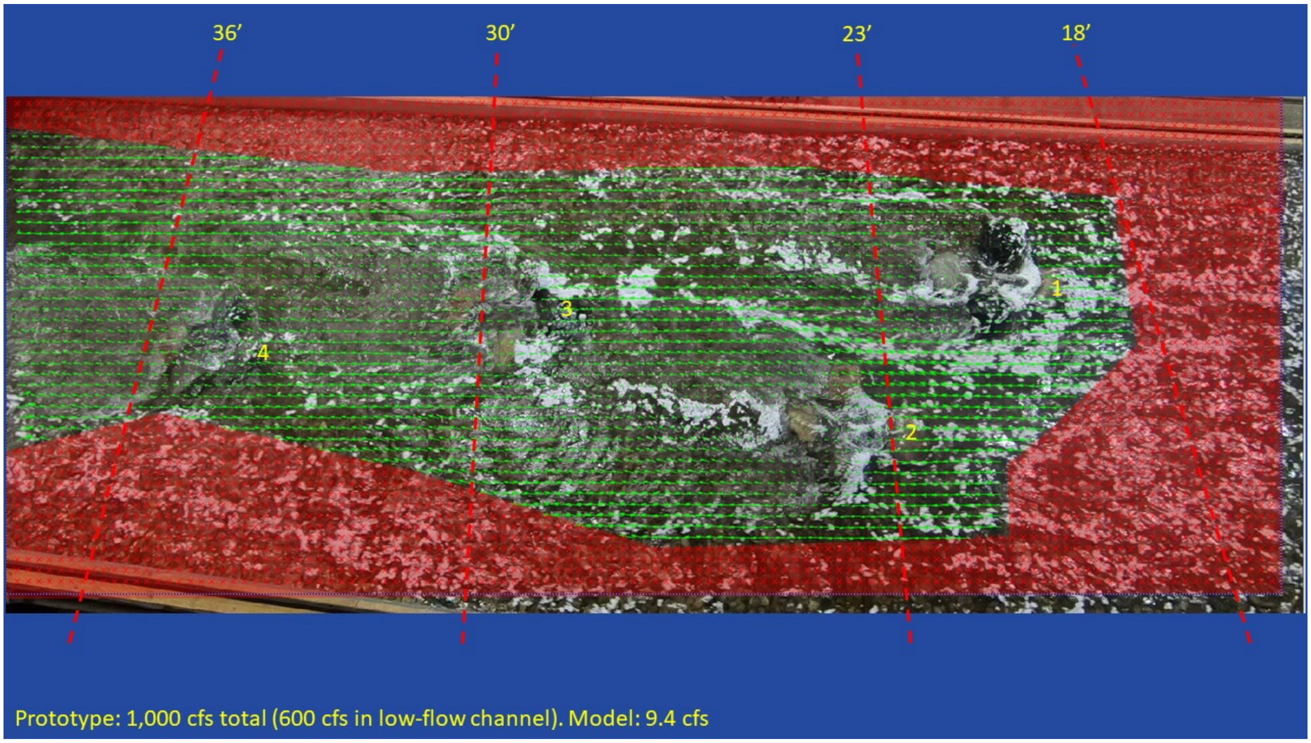

Figure C 35. PIVLab output of velocity vectors at 600 cfs at the diamond, high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

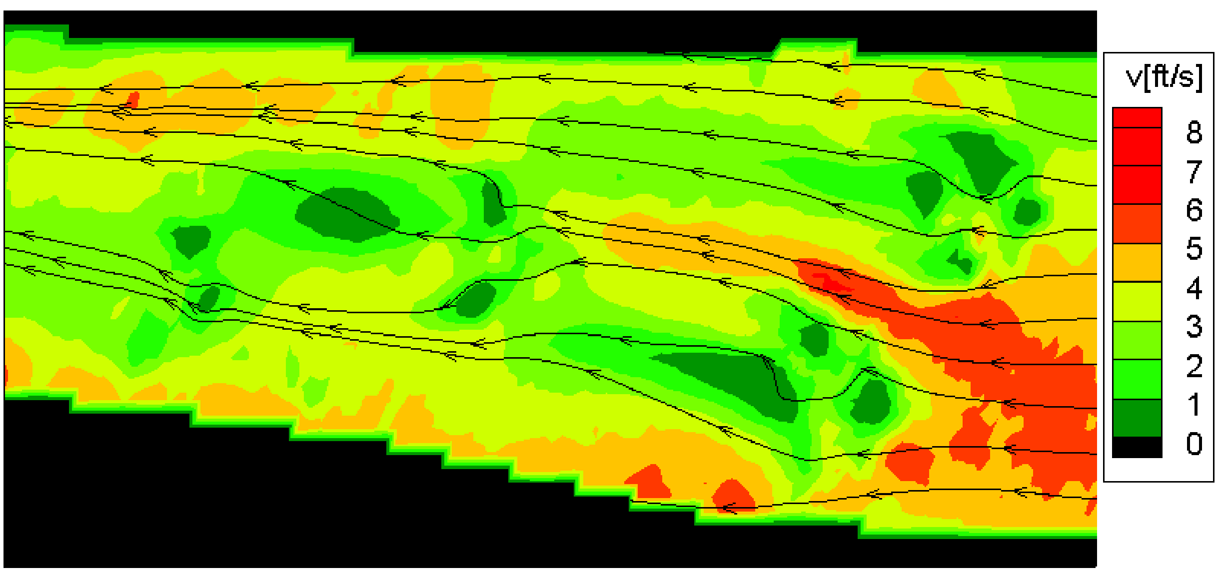

Figure C 36. TecPlot output for velocity at 600 cfs at the diamond, high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

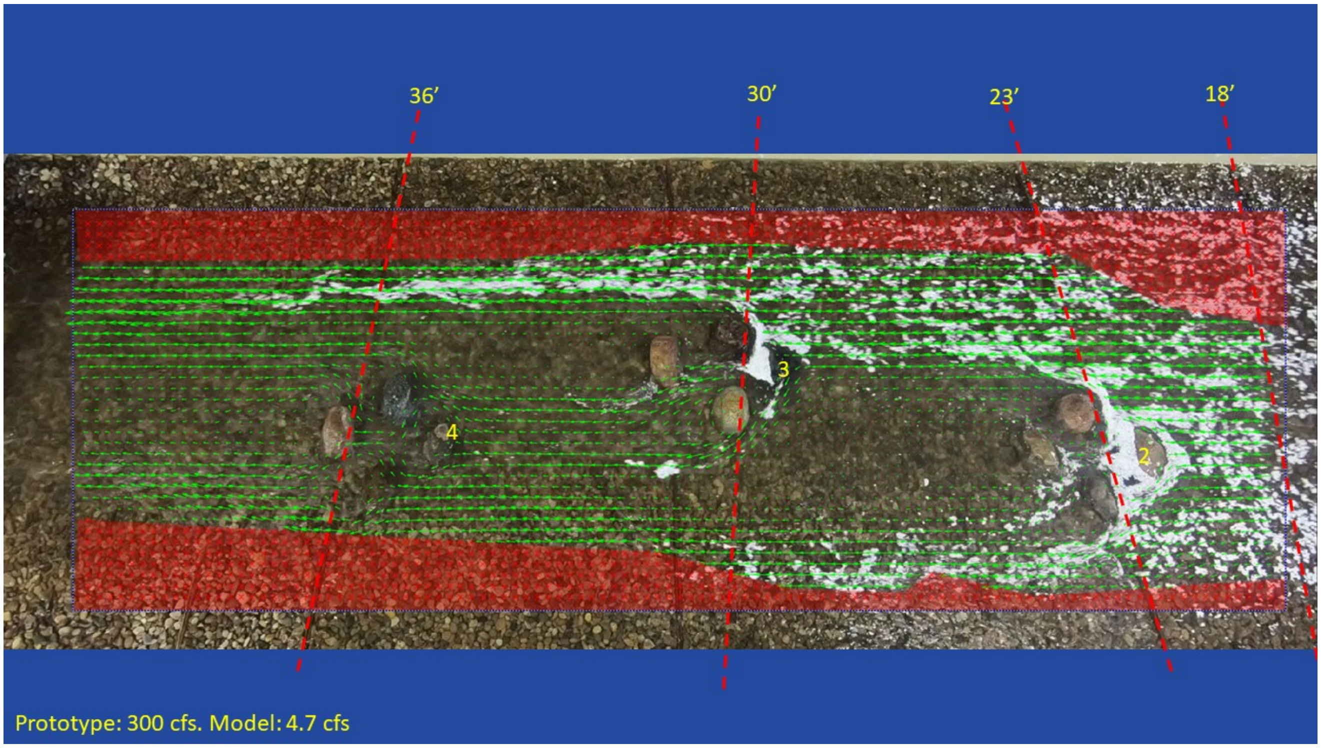

Figure C 37. PIVLab output of velocity vectors at 300 cfs at the diamond, medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

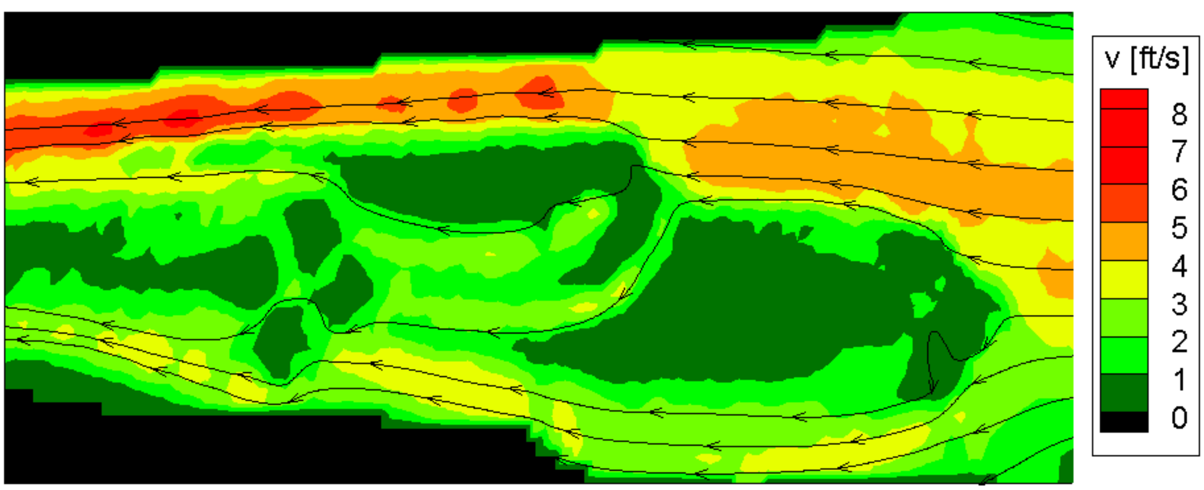

Figure C 38. TecPlot output for velocity at 300 cfs at the diamond, medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

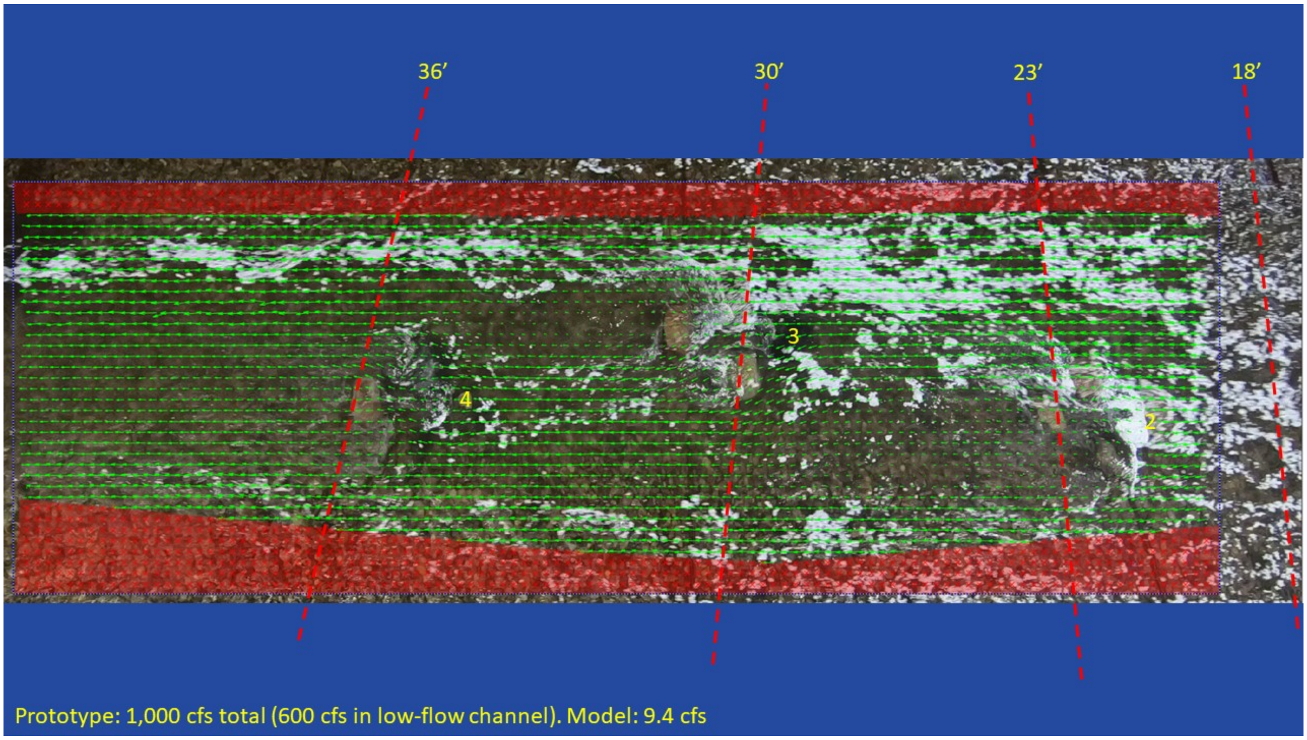

Figure C 39. PIVLab output of velocity vectors at 600 cfs at the diamond, medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

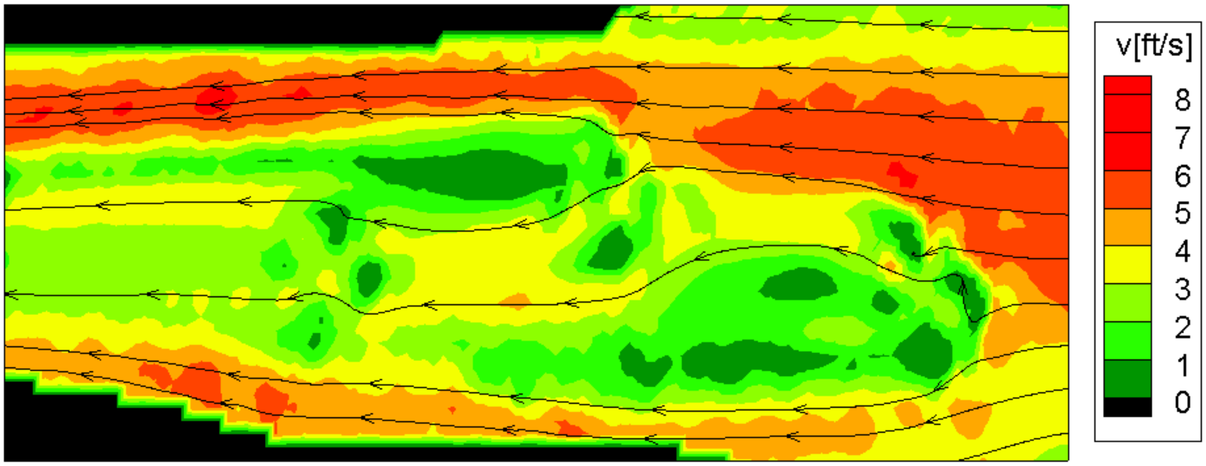

Figure C 40. TecPlot output for velocity at 600 cfs at the diamond, medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

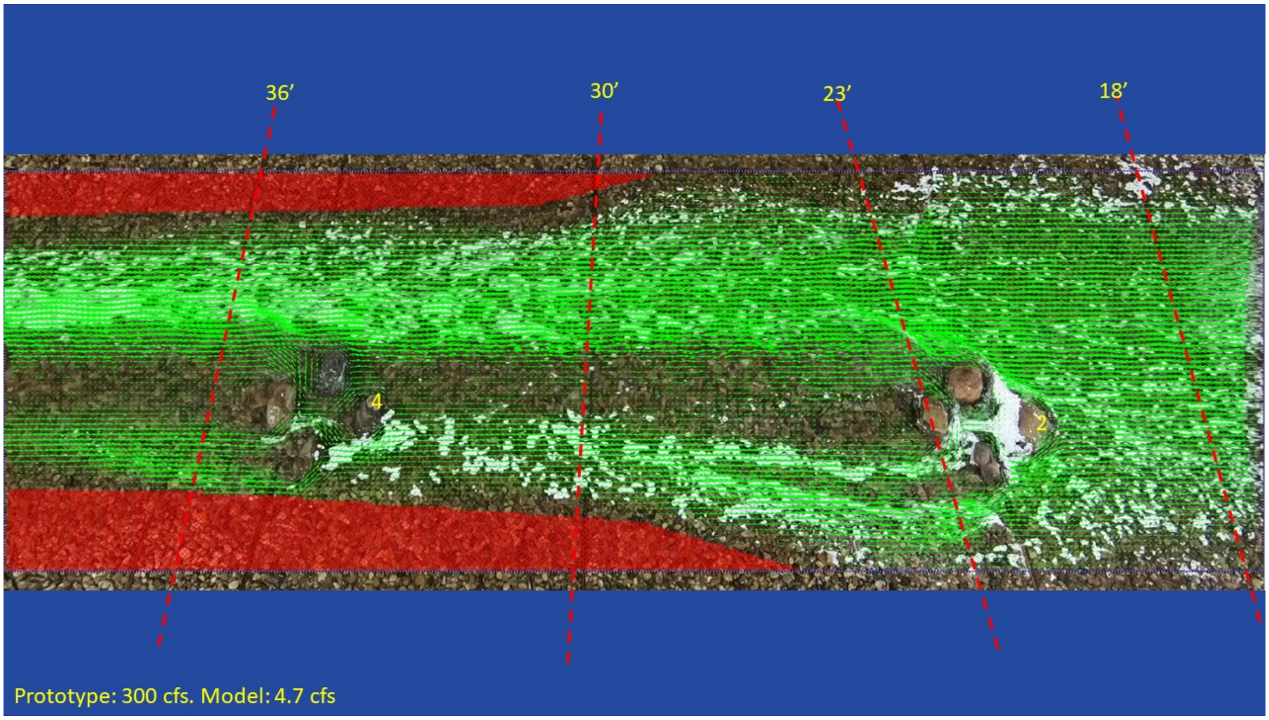

Figure C 41. PIVLab output of velocity vectors at 300 cfs at the diamond, low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

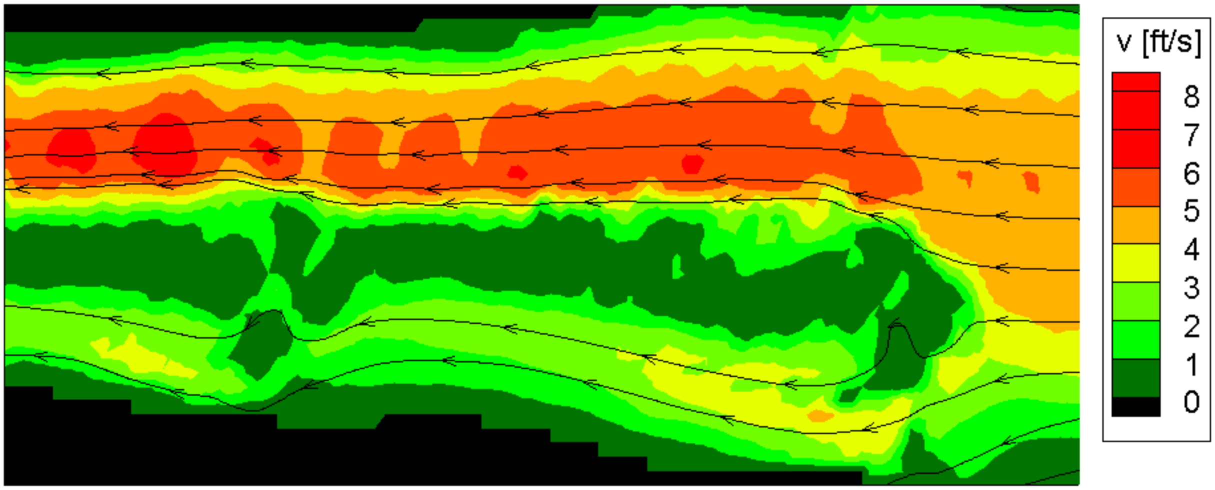

Figure C 42. TecPlot output for velocity at 300 cfs at the diamond, low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

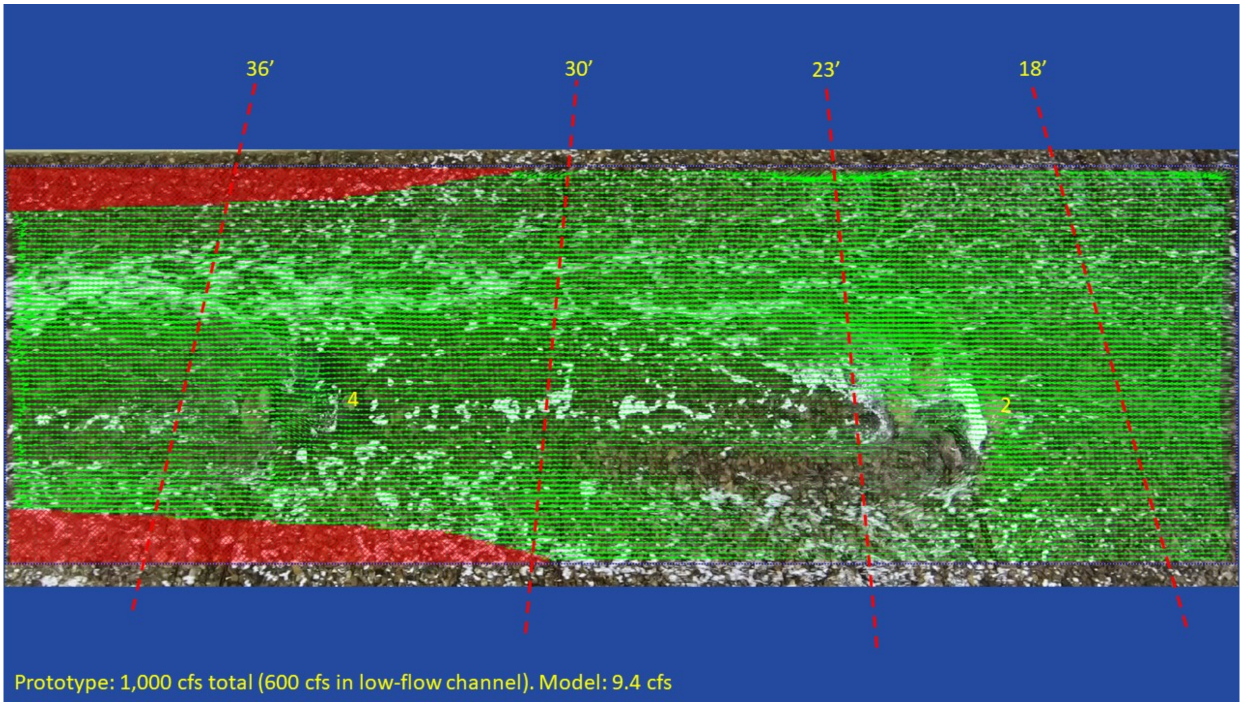

Figure C 43. PIVLab output of velocity vectors at 600 cfs at the diamond, low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

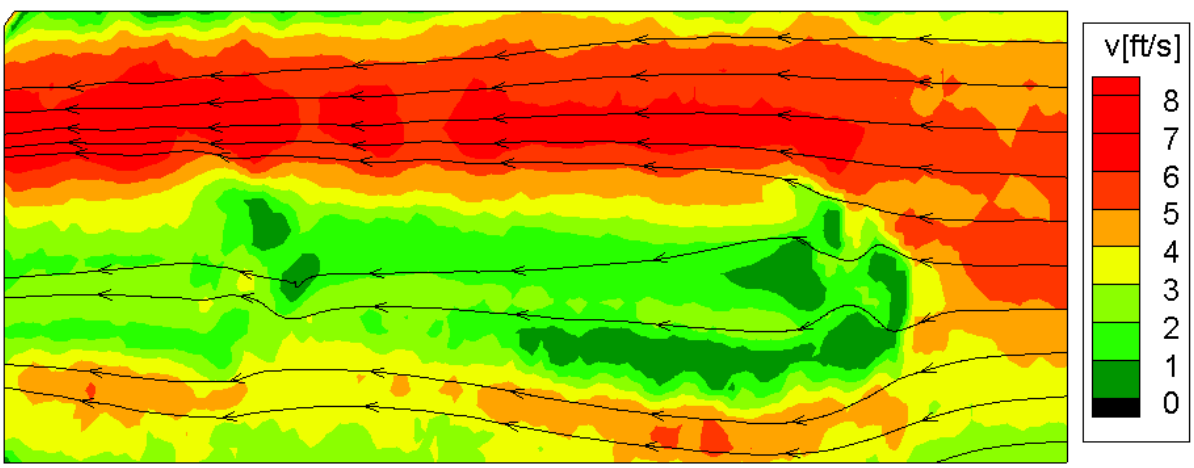

Figure C 44. TecPlot output for velocity at 600 cfs at the diamond, low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

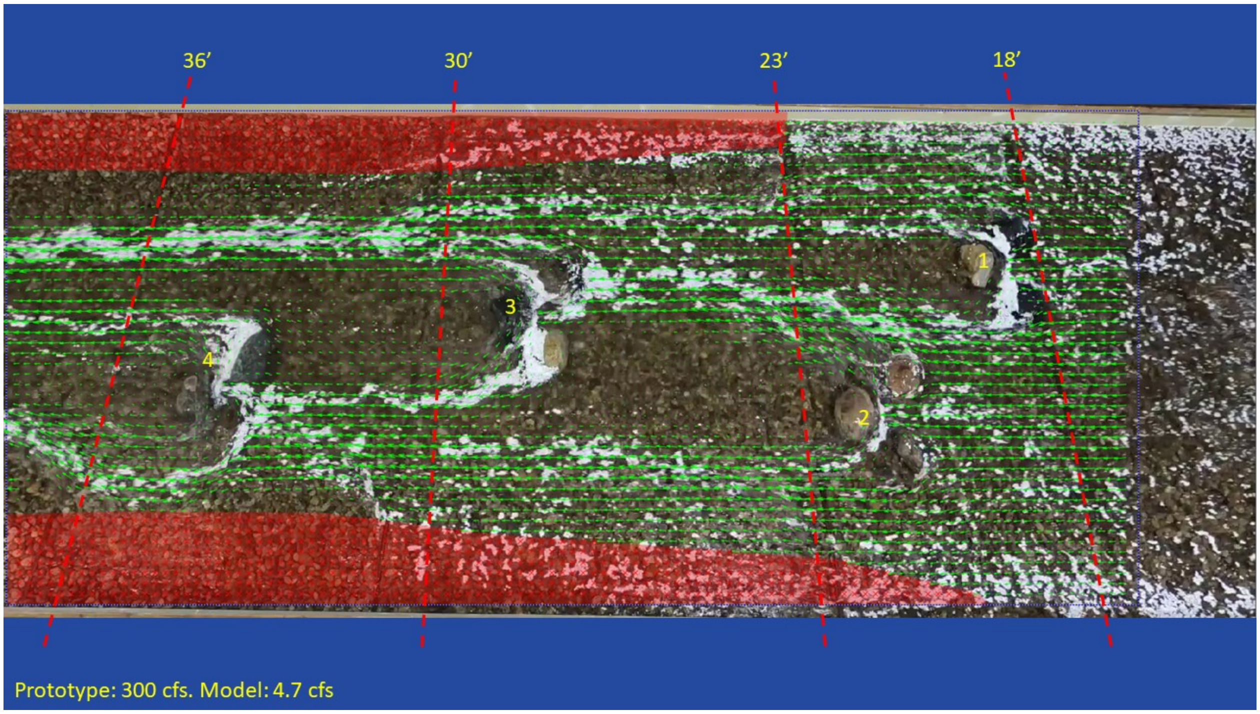

Figure C 45. PIVLab output of velocity vectors at 300 cfs at the downstream "V", high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

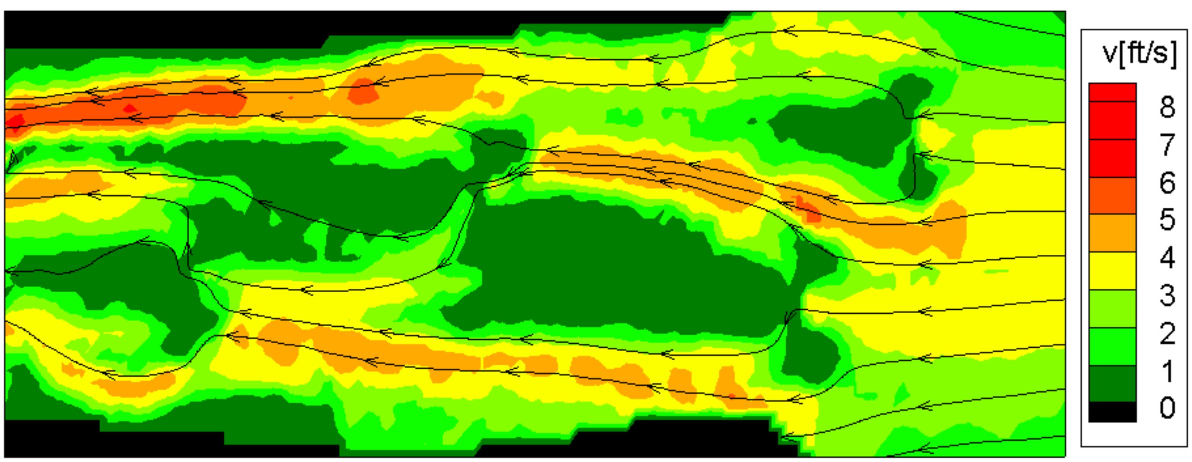

Figure C 46. TecPlot output for velocity at 300 cfs at the downstream "V", high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

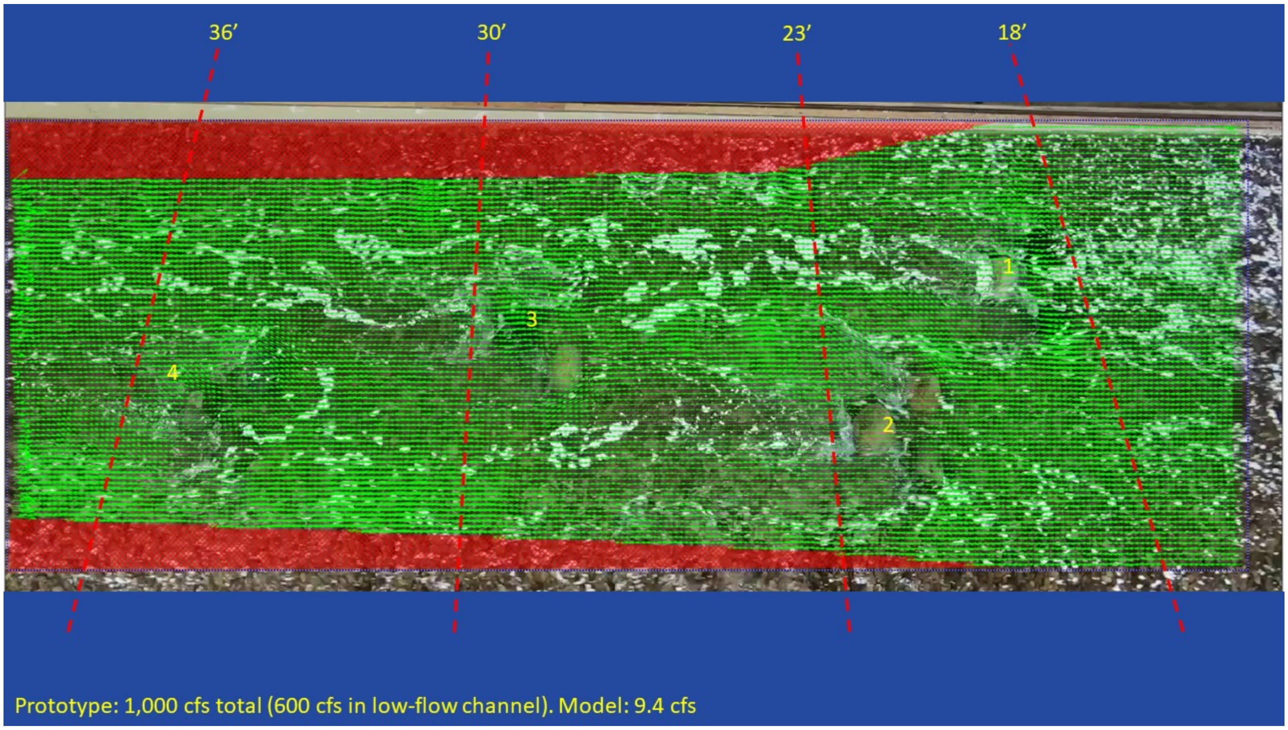

Figure C 47. PIVLab output of velocity vectors at 600 cfs at the downstream "V", high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

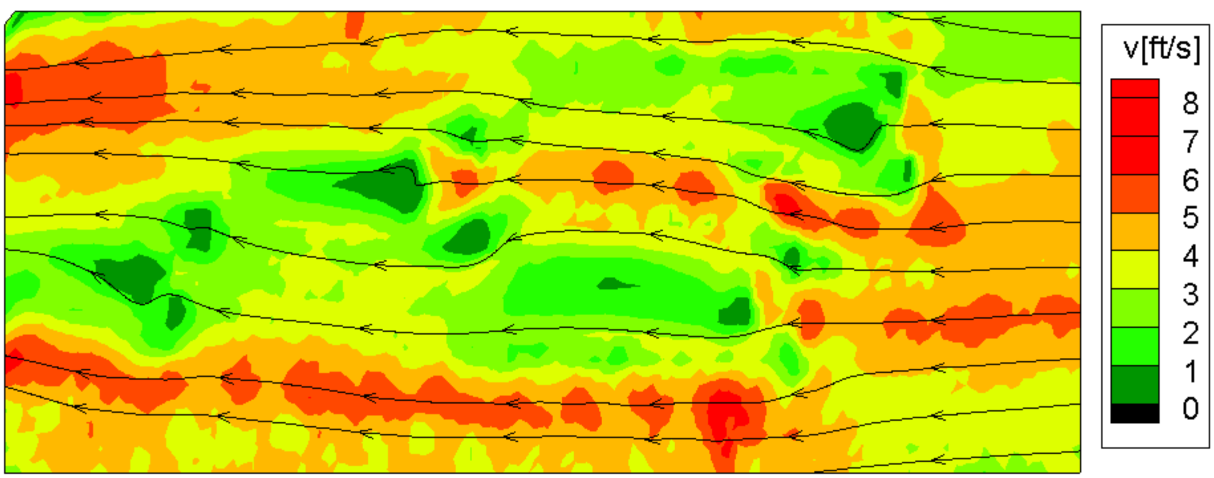

Figure C 48. TecPlot output for velocity at 600 cfs at the downstream "V", high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

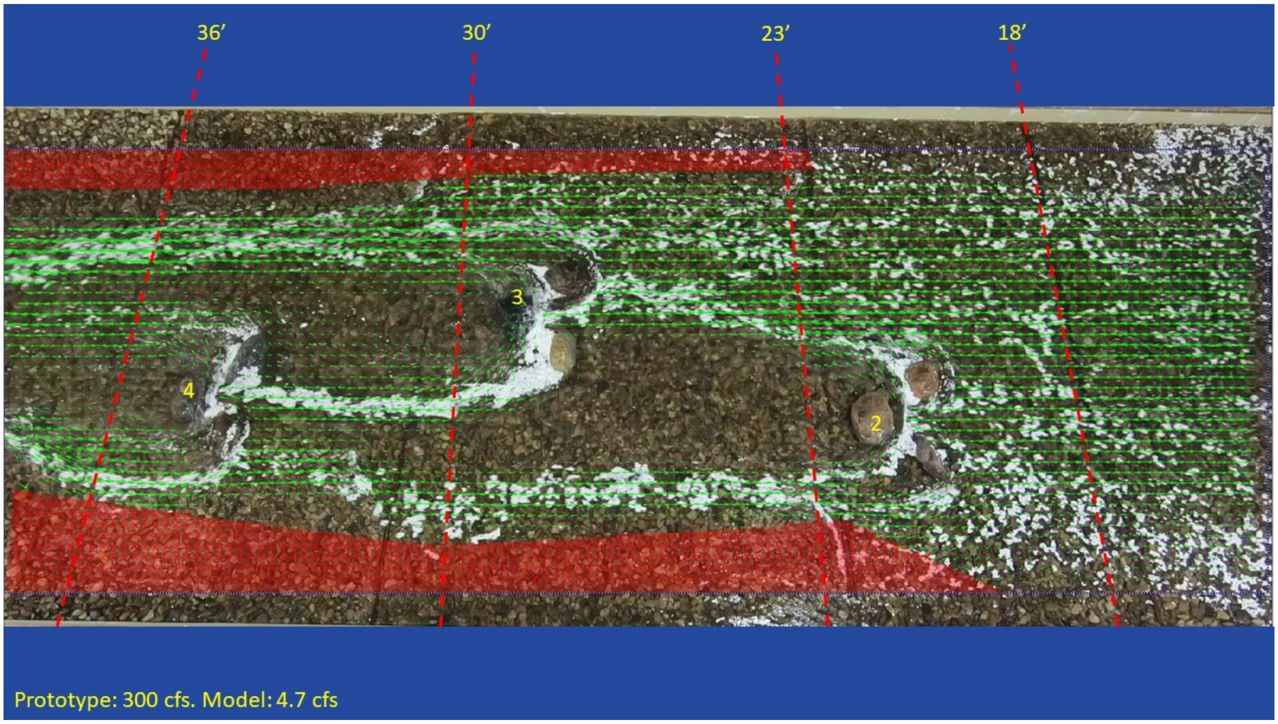

Figure C 49. PIVLab output of velocity vectors at 300 cfs at the downstream "V", medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

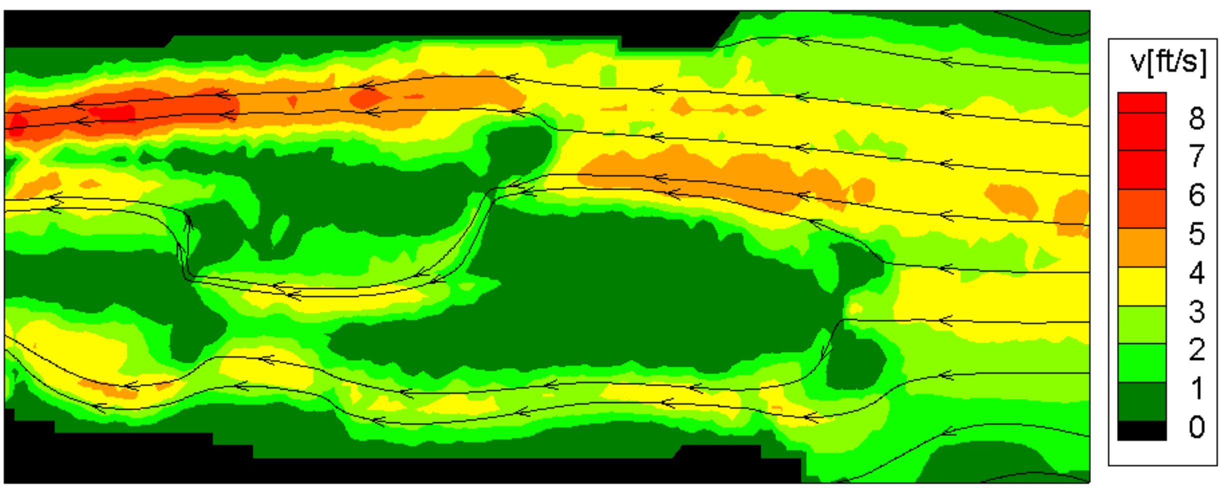

Figure C 50. TecPlot output for velocity at 300 cfs at the downstream "V", medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

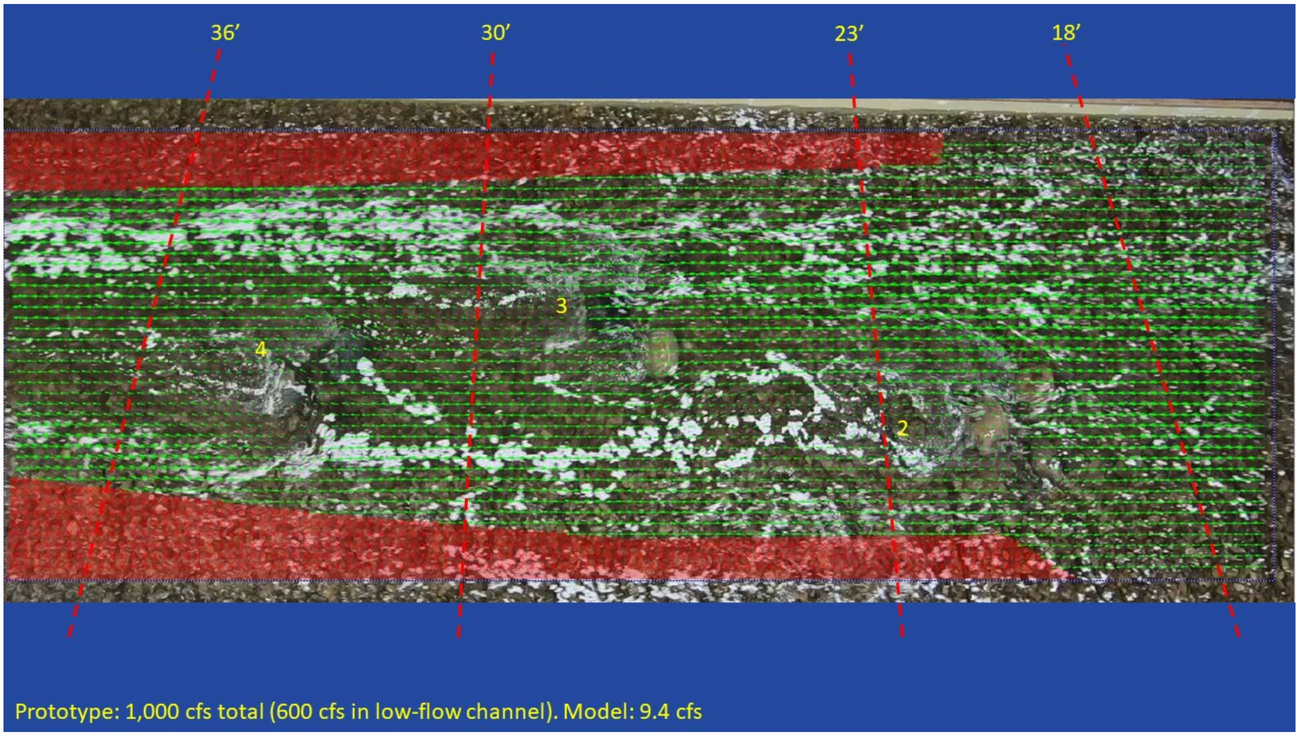

Figure C 51. PIVLab output of velocity vectors at 600 cfs at the downstream "V", medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

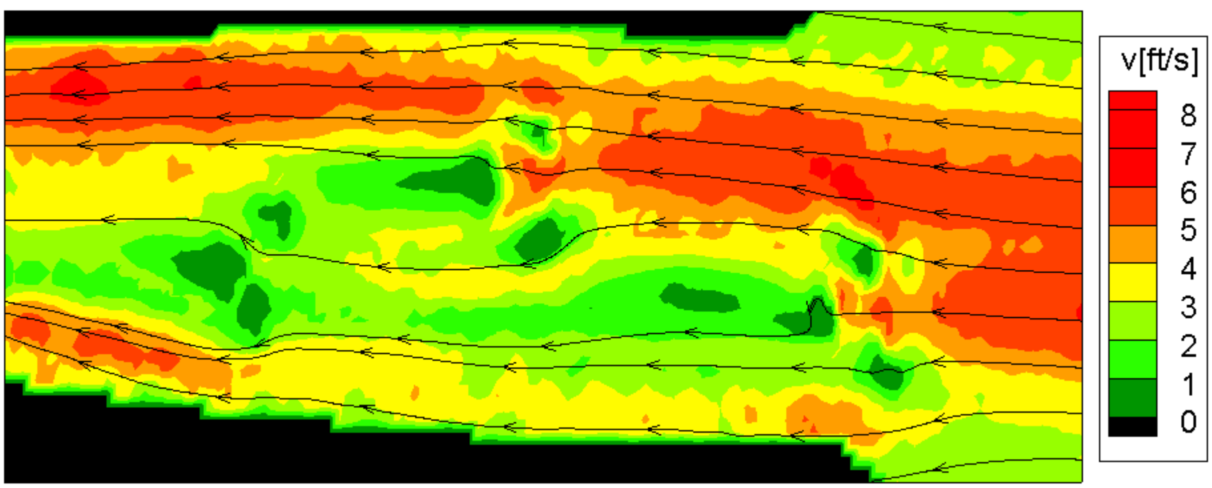

Figure C 52. TecPlot output for velocity at 600 cfs at the downstream "V", high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

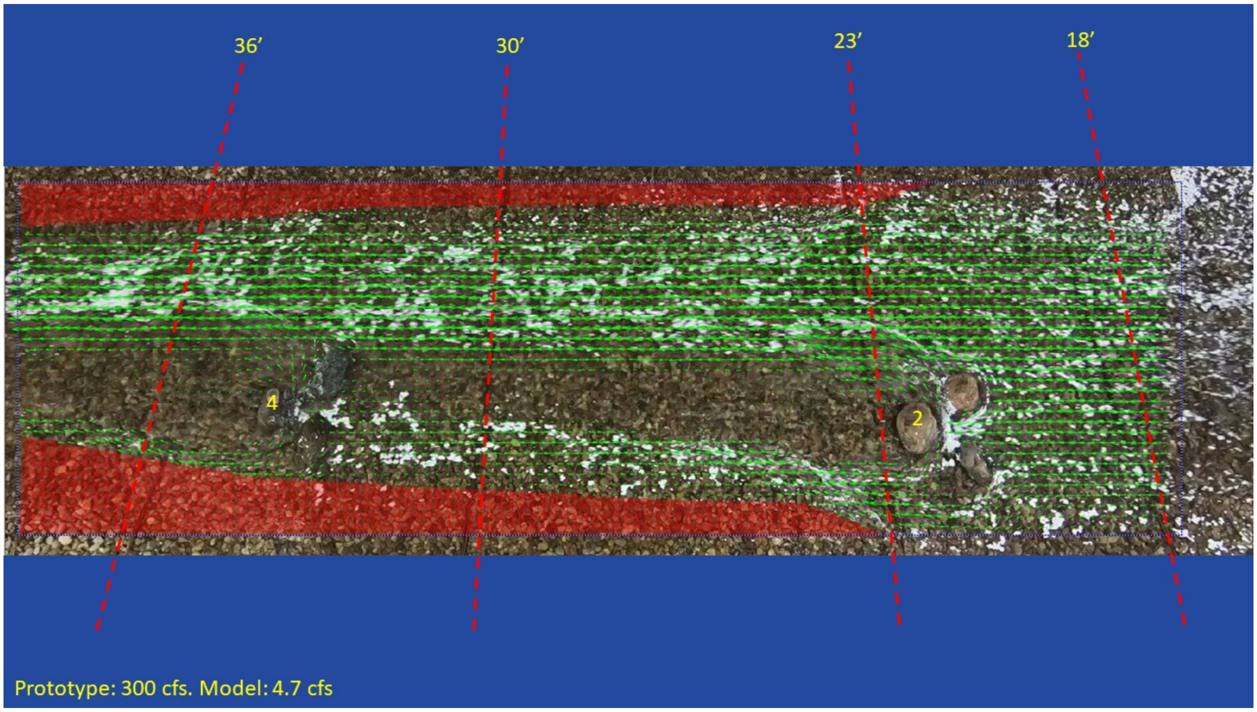

Figure C 53. PIVLab output of velocity vectors at 300 cfs at the downstream "V", low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

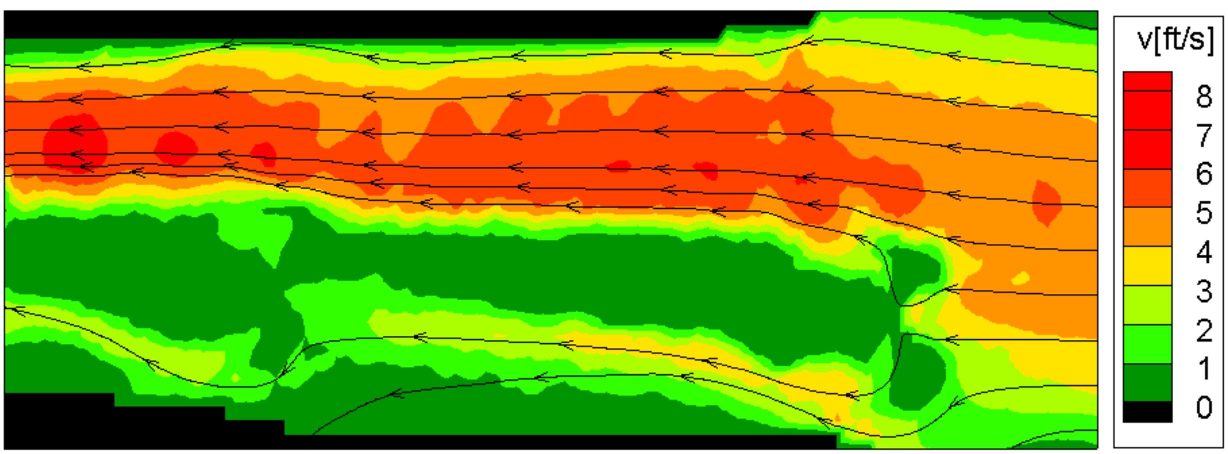

Figure C 54. TecPlot output for velocity at 300 cfs at the downstream "V", low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

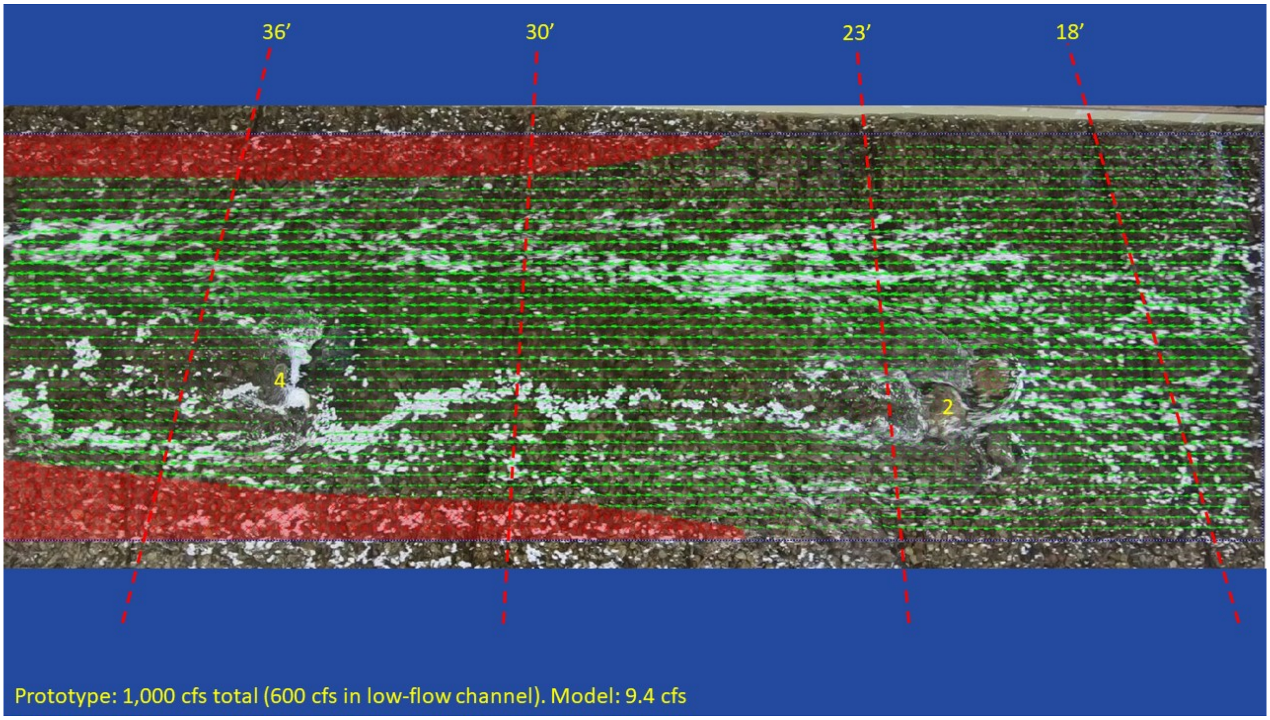

Figure C 55. PIVLab output of velocity vectors at 600 cfs at the downstream "V", low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

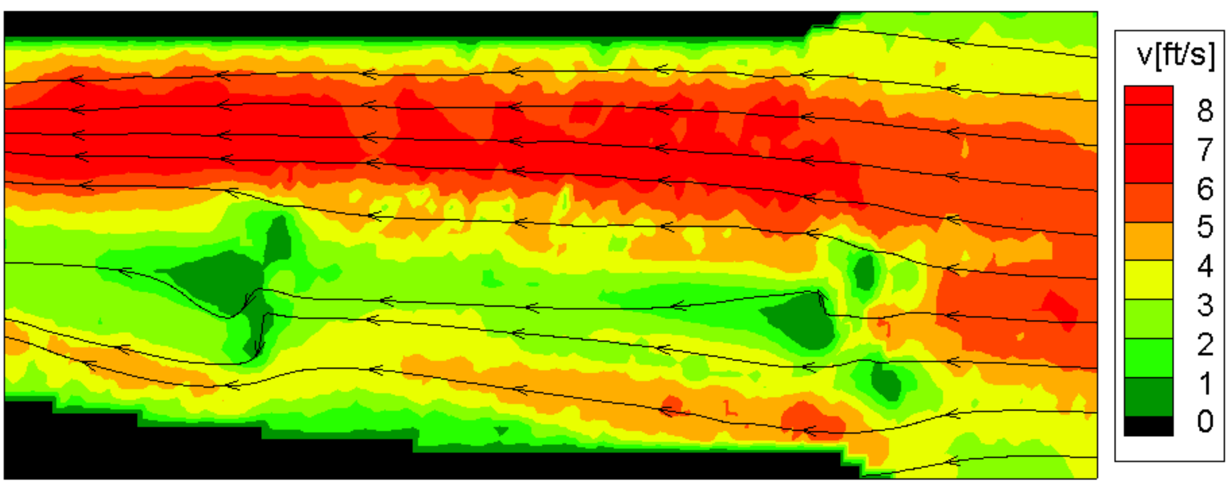

Figure C 56. TecPlot output for velocity at 600 cfs at the downstream "V", high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

Appendix D – Hydraulic Modeling Results from WinADV

Table D 1. PIVLab Baseline (without rocks) ADV results for the resultant velocity (ft/s) and the water depth in prototype (ft)

Baseline ADV Measurements 300cfs

Location	Prototype Velocity ft/s	Prototype Depth ft
18ft Rt	5.16	1.54
18ft Center	5.12	1.56
18ft Left	4.66	1.55
23ft Rt	5.32	1.04
23ft Center	6.38	1.50
23ft Left	4.71	1.42
30ft Rt	4.91	1.26
30ft Center	5.35	1.81
30ft Left	3.91	1.40
36ft Rt	3.40	1.55
36ft Center	4.99	2.11
36ft Left	4.18	1.34

Baseline ADV Measurements 600cfs

Location	Prototype Velocity ft/s	Prototype Depth ft
18ft Rt	5.52	1.71
18ft Center Rt	6.18	2.39
18ft Center Left	6.09	2.03
18ft Left	4.36	1.47
23ft Rt	5.76	1.26
23ft Center Rt	6.70	2.13
23ft Center Left	6.82	1.81
23ft Left	4.63	1.30
30 Rt	4.83	1.59
30ft Center Rt	6.49	2.62
30ft Center Left	6.74	2.31
30ft Left	4.85	1.36
36 Rt	3.57	1.33
36 Center Rt	7.12	2.64
36ft Center Left	5.41	2.74
36ft Left	3.46	1.65

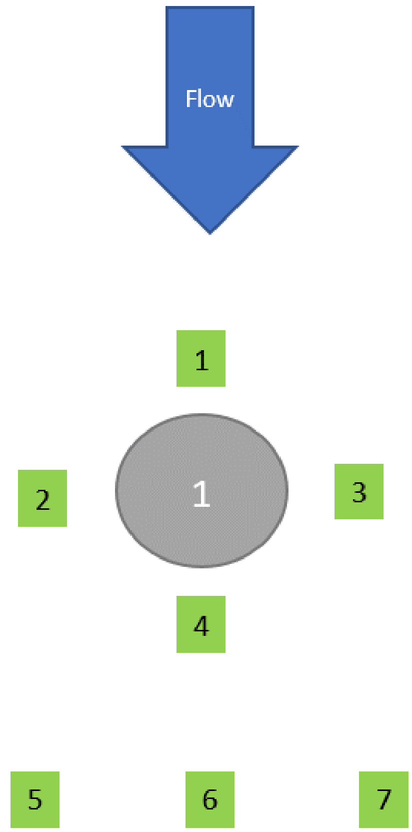

Figure D 1. Location of ADV measurements taken for a single rock configuration

Table D 2. ADV results for single rock configuration at the lowest density (2 rocks) at both flow rates.

Single Rock ADV: 300cfs Low Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	5.14	1.48
	18ft Center	4.85	1.57
	18ft Left	4.27	1.42
	23 Rt	5.40	1.39
	23 Center	5.23	1.56
	30 Rt	4.86	1.30
	30 Center	4.93	1.93
	30 Left	4.31	1.19
	36 Rt	4.50	1.44
	36 Center	5.45	1.93
Rock 4	1) Upstream Center	2.14	1.85
	2) Upstream Rt	5.99	1.65
	3) Upstream Left	3.86	1.38
	4) Downstream	0.46	1.27
	5) 18" Downstream Rt	4.83	1.73
	6) 18" Downstream Center	0.97	1.64
	7) 18" Downstream Left	4.13	1.08
Rock 2	1) Upstream Center	2.71	1.67
	2) Upstream Rt	5.32	1.60
	3) Upstream Left	3.95	1.78
	4) Downstream	0.24	0.68
	5) 18" Downstream Rt	5.46	1.30
	6) 18" Downstream Center	2.11	1.23
	7) 18" Downstream Left	1.24	0.89

Single Rock ADV: 600cfs Low Density

	Location	Prototype Velocity ft/s	Prototyp Depth ft
Baseline	18ft Rt	5.43	2.02
	18ft Center Rt	5.79	2.07
	18ft Center Left	6.06	2.16
	18ft Left	4.38	1.50
	23 Rt	6.44	1.63
	23 Center Rt	5.93	2.16
	30 Rt	4.71	1.69
	30ft Center Rt	6.64	2.18
	30ft Center Left	5.59	2.31
	30 Left	4.68	1.38
	36 Rt	5.68	1.47
	36 Center Rt	7.17	2.27
Rock 4	1) Upstream Center	3.17	2.48
	2) Upstream Rt	6.64	2.44
	3) Upstream Left	4.73	2.02
	4) Downstream	1.96	2.01
	5) 18" Downstream Rt	7.28	2.58
	6) 18" Downstream Center	2.36	2.23
	7) 18" Downstream Left	6.04	1.68
Rock 2	1) Upstream Center	4.26	2.15
	2) Upstream Rt	6.20	2.31
	3) Upstream Left	5.06	1.51
	4) Downstream	2.85	1.65
	5) 18" Downstream Rt	8.17	1.97
	6) 18" Downstream Center	3.25	1.88
	7) 18" Downstream Left	5.55	1.55

Table D 3. ADV results for single rock configuration at the medium density (4 rocks) at both flow rates.

Single Rock ADV: 300cfs Medium Density

Group	Location	Prototype Velocity ft/s	Prototype Depth *** ft
Baseline	18ft Rt	3.24	1.93
	18ft Center	3.63	1.68
	18ft Left	3.49	
	23 Rt	2.87	1.64
	23 Center	5.54	1.61
	30 Left	3.22	1.29
	36 Rt	3.30	1.77
	36 Center	4.88	1.84
Rock 4	1) Upstream Center	2.35	1.77
	2) Upstream Rt	5.28	
	3) Upstream Left	4.11	
	4) Downstream	0.30	1.31
	5) 18" Downstream Rt	4.93	
	6) 18" Downstream Center	1.68	
	7) 18" Downstream Left	3.58	
Rock 3	1) Upstream Center	2.72	1.97
	2) Upstream Rt	3.69	
	3) Upstream Left	4.80	
	4) Downstream	0.59	1.34
	5) 18" Downstream Rt	5.48	
	6) 18" Downstream Center	1.93	
	7) 18" Downstream Left	6.26	
Rock 2	1) Upstream Center	2.78	1.73
	2) Upstream Rt	3.93	
	3) Upstream Left	4.33	
	4) Downstream	0.94	1.21
	5) 18" Downstream Rt	5.46	
	6) 18" Downstream Center	0.67	
	7) 18" Downstream Left	3.26	

Single Rock ADV: 600cfs Medium Density

Group	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	4.77	2.03
	18ft Center Rt	4.97	2.23
	18ft Center Left	5.36	2.27
	18ft Left	4.36	1.50
	23 Rt	4.97	1.47
	23 Center Rt	4.87	2.10
	30 Rt	5.07	2.11
	30 Left	5.32	1.29
	36 Rt	4.92	1.81
	36 Center Rt	6.27	2.78
Rock 4	1) Upstream Center	4.01	2.57
	2) Upstream Rt	6.64	2.76
	3) Upstream Left	3.99	1.68
	4) Downstream	2.37	2.26
	5) 18" Downstream Rt	6.33	2.85
	6) 18" Downstream Center	3.74	
	7) 18" Downstream Left	4.68	2.58
Rock 3	1) Upstream Center	4.65	2.36
	2) Upstream Rt	4.29	2.31
	3) Upstream Left	5.66	2.28
	4) Downstream	4.04	1.94
	5) 18" Downstream Rt	5.59	2.39
	6) 18" Downstream Center	4.70	2.83
	7) 18" Downstream Left	5.97	2.39
Rock 2	1) Upstream Center	5.16	2.32
	2) Upstream Rt	5.51	2.45
	3) Upstream Left	5.06	1.76
	4) Downstream	2.63	1.34
	5) 18" Downstream Rt	7.34	1.78
	6) 18" Downstream Center	1.58	1.98
	7) 18" Downstream Left	5.02	1.47

Rock 1	1) Upstream Center	2.63	2.01
	2) Upstream Rt	4.60	
	3) Upstream Left	4.57	
	4) Downstream	0.60	1.39
	5) 18" Downstream Rt	4.42	
	6) 18" Downstream Center	1.31	
	7) 18" Downstream Left	6.07	

Rock 1	1) Upstream Center	4.69	2.51
	2) Upstream Rt	5.24	1.89
	3) Upstream Left	4.96	2.52
	4) Downstream	2.67	1.99
	5) 18" Downstream Rt	4.37	1.48
	6) 18" Downstream Center	3.44	2.09
	7) 18" Downstream Left	2.55	2.15

*** At the time of trial, depths were not consistently collected at all points.

Table D 4. ADV results for single rock configuration at the medium-high density (6 rocks) at both flow rates.

Single Rock ADV: 300cfs Medium High Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	2.85	1.78
	18ft Center	4.23	1.68
	18ft Left	3.49	1.40
	23 Rt	2.28	1.18
	23 Center	5.45	1.57
	30 Left	4.29	1.60
	36 Rt	2.42	1.12
	36 Center	4.54	1.92
Rock 6	1) Upstream Center	3.46	2.24
	2) Upstream Rt	3.87	1.57
	3) Upstream Left	4.82	1.95
	4) Downstream	0.38	1.65
	5) 18" Downstream Rt	2.32	0.97
	6) 18" Downstream Center	0.39	1.42
	7) 18" Downstream Left	5.56	2.03
Rock 5	1) Upstream Center	2.56	2.28
	2) Upstream Rt	4.56	1.36
	3) Upstream Left	5.97	
	4) Downstream	0.67	1.52
	5) 18" Downstream Rt	4.72	1.33
	6) 18" Downstream Center	1.16	1.50
	7) 18" Downstream Left	6.49	1.78
Rock 4	1) Upstream Center	2.62	2.16
	2) Upstream Rt	6.95	1.98
	3) Upstream Left	4.76	1.22
	4) Downstream	0.30	1.64
	5) 18" Downstream Rt	6.61	1.78
	6) 18" Downstream Center	1.49	1.64
	7) 18" Downstream Left	4.83	1.35

Single Rock ADV: 600cfs Medium High Density

	Location	Prototype Velocity ft/s	Prototyp Depth ft
Baseline	18ft Rt	4.02	2.03
	18ft Center Rt	4.85	2.26
	18ft Center Left	4.82	2.10
	18ft Left	4.01	1.68
	23 Rt	3.40	1.99
	23 Center Rt	6.35	2.16
	30 Rt	5.45	1.50
	30 Left	5.32	1.59
	36 Rt	5.03	1.77
	36 Center Rt	5.26	3.10
Rock 6	1) Upstream Center	4.13	2.72
	2) Upstream Rt	5.62	2.27
	3) Upstream Left	4.88	2.49
	4) Downstream	2.06	2.28
	5) 18" Downstream Rt	5.75	1.68
	6) 18" Downstream Center	2.95	2.40
	7) 18" Downstream Left	5.60	2.69
Rock 5	1) Upstream Center	7.21	2.60
	2) Upstream Rt	2.29	1.81
	3) Upstream Left	5.18	
	4) Downstream	4.08	1.92
	5) 18" Downstream Rt	5.67	1.88
	6) 18" Downstream Center	2.35	2.01
	7) 18" Downstream Left	8.00	
Rock 4	1) Upstream Center	4.15	2.62
	2) Upstream Rt	7.57	2.61
	3) Upstream Left	5.62	1.90
	4) Downstream	2.34	2.16
	5) 18" Downstream Rt	7.67	2.40
	6) 18" Downstream Center	3.88	2.32

Rock 3	1) Upstream Center	1.40	1.98
	2) Upstream Rt	3.91	2.31
	3) Upstream Left	6.26	1.47
	4) Downstream	0.69	1.85
	5) 18" Downstream Rt	4.14	1.88
	6) 18" Downstream Center	1.79	2.14
	7) 18" Downstream Left	4.80	2.24
Rock 2	1) Upstream Center	2.57	1.92
	2) Upstream Rt	4.40	1.94
	3) Upstream Left	4.31	1.12
	4) Downstream	0.30	1.08
	5) 18" Downstream Rt	4.18	1.97
	6) 18" Downstream Center	0.39	1.51
	7) 18" Downstream Left	4.44	1.12
Rock 1	1) Upstream Center	2.71	1.97
	2) Upstream Rt	4.22	1.26
	3) Upstream Left	3.57	2.05
	4) Downstream	0.87	1.51
	5) 18" Downstream Rt	2.25	1.02
	6) 18" Downstream Center	1.31	1.36
	7) 18" Downstream Left	4.87	1.73

Distance not taken due to impact from Rock 2 creating uneven surface.

	7) 18" Downstream Left	7.01	2.05
Rock 3	1) Upstream Center	3.11	2.52
	2) Upstream Rt	4.53	2.47
	3) Upstream Left	6.77	2.20
	4) Downstream	0.86	2.27
	5) 18" Downstream Rt	5.51	2.52
	6) 18" Downstream Center	2.65	2.64
	7) 18" Downstream Left	6.38	2.79
Rock 2	1) Upstream Center	4.44	2.49
	2) Upstream Rt	5.36	2.52
	3) Upstream Left	5.57	1.61
	4) Downstream	1.44	1.56
	5) 18" Downstream Rt	5.68	2.44
	6) 18" Downstream Center	1.12	2.07
	7) 18" Downstream Left	5.10	1.50
Rock 1	1) Upstream Center	4.70	2.74
	2) Upstream Rt	2.93	1.88
	3) Upstream Left	5.26	2.70
	4) Downstream	3.65	1.95
	5) 18" Downstream Rt	5.04	1.63
	6) 18" Downstream Center	2.46	1.98
	7) 18" Downstream Left	6.05	2.09

Distance not taken due to impact from Rock 2 creating uneven surface.

Table D 5. ADV results for single rock configuration at the high density (8 rocks) at both flow rates.

Single Rock ADV: 300cfs High Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	3.25	1.93
	18ft Center	3.95	1.78
	18ft Left	3.80	1.54
	23 Rt	1.92	1.55
	23 Center	5.26	1.94
	30 Left	2.41	1.86
	36 Rt	2.58	1.73
	36 Center	5.90	1.94
Rock 8	1) Upstream Center	1.38	2.23
	2) Upstream Rt	5.56	2.19
	3) Upstream Left	4.73	1.25
	4) Downstream	0.38	1.59
	5) 18" Downstream Rt	5.84	2.10
	6) 18" Downstream Center	1.21	1.55
	7) 18" Downstream Left	5.24	1.02
Rock 7	1) Upstream Center	0.41	1.73
	2) Upstream Rt	5.81	1.74
	3) Upstream Left	4.29	1.15
	4) Downstream	0.73	1.30
	5) 18" Downstream Rt	5.19	1.61
	6) 18" Downstream Center	0.92	1.61
	7) 18" Downstream Left	1.02	0.92
Rock 6	1) Upstream Center	3.08	2.18
	2) Upstream Rt	3.92	1.76
	3) Upstream Left	5.03	2.23
	4) Downstream	0.45	1.60
	5) 18" Downstream Rt	6.24	1.15
	6) 18" Downstream Center	0.45	1.77
	7) 18" Downstream Left	5.07	1.99

Single Rock ADV: 600cfs High Density

	Location	Prototype Velocity ft/s	Prototyp Depth ft
Baseline	18ft Rt	4.54	2.09
	18ft Center Rt	4.94	2.39
	18ft Center Left	4.71	2.24
	18ft Left	4.71	1.74
	23 Rt	3.18	2.13
	23 Center Rt	6.13	2.48
	30 Rt	4.73	1.89
	30 Left	4.68	1.98
	36 Rt	6.08	1.78
	36 Center Rt	5.55	2.56
Rock 8	1) Upstream Center	3.02	2.44
	2) Upstream Rt	6.84	3.14
	3) Upstream Left	4.96	1.80
	4) Downstream	1.14	2.19
	5) 18" Downstream Rt	6.64	2.81
	6) 18" Downstream Center	0.83	2.31
	7) 18" Downstream Left	5.77	1.97
Rock 7	1) Upstream Center	1.75	2.41
	2) Upstream Rt	5.84	2.57
	3) Upstream Left	5.03	1.60
	4) Downstream	0.36	1.95
	5) 18" Downstream Rt	6.33	2.20
	6) 18" Downstream Center	2.27	2.41
	7) 18" Downstream Left	5.39	1.54
Rock 6	1) Upstream Center	5.32	2.87
	2) Upstream Rt	5.33	2.24
	3) Upstream Left	3.12	2.93
	4) Downstream	4.42	2.06
	5) 18" Downstream Rt	5.94	1.93
	6) 18" Downstream Center	3.99	2.35
	7) 18" Downstream Left	6.19	2.78

Rock 5	1) Upstream Center	2.61	2.36
	2) Upstream Rt	5.17	1.55
	3) Upstream Left	5.55	1.81
	4) Downstream	0.14	1.67
	5) 18" Downstream Rt	4.65	1.57
	6) 18" Downstream Center	0.68	1.43
	7) 18" Downstream Left	6.41	1.94
Rock 4	1) Upstream Center	1.75	1.92
	2) Upstream Rt	7.34	1.81
	3) Upstream Left	4.63	1.30
	4) Downstream	0.06	1.39
	5) 18" Downstream Rt	6.73	1.88
	6) 18" Downstream Center	2.79	1.55
	7) 18" Downstream Left	4.97	1.02
Rock 3	1) Upstream Center	1.39	2.06
	2) Upstream Rt	3.79	1.64
	3) Upstream Left	5.18	1.74
	4) Downstream	0.43	1.95
	5) 18" Downstream Rt	4.41	1.84
	6) 18" Downstream Center	2.58	1.98
	7) 18" Downstream Left		0.00
Rock 2	1) Upstream Center	2.49	1.90
	2) Upstream Rt	4.37	2.02
	3) Upstream Left	4.31	1.63
	4) Downstream	0.24	1.22
	5) 18" Downstream Rt	3.46	2.13
	6) 18" Downstream Center	0.28	1.68
	7) 18" Downstream Left	3.23	1.34
Rock 1	1) Upstream Center	2.65	2.07
	2) Upstream Rt	4.41	1.39
	3) Upstream Left	4.16	2.01
	4) Downstream	0.80	1.69
	5) 18" Downstream Rt	4.14	1.17
	6) 18" Downstream Center	1.16	1.57
	7) 18" Downstream Left	5.65	1.72

Rock 5	1) Upstream Center	4.27	2.70
	2) Upstream Rt	5.37	2.02
	3) Upstream Left	6.94	2.90
	4) Downstream	2.57	2.19
	5) 18" Downstream Rt	5.38	2.13
	6) 18" Downstream Center	2.92	2.27
	7) 18" Downstream Left	7.58	2.86
Rock 4	1) Upstream Center	2.23	2.61
	2) Upstream Rt	7.21	2.60
	3) Upstream Left	5.74	2.05
	4) Downstream	0.86	2.37
	5) 18" Downstream Rt	6.48	2.69
	6) 18" Downstream Center	3.82	2.57
	7) 18" Downstream Left	5.97	1.86
Rock 3	1) Upstream Center	3.38	2.72
	2) Upstream Rt	4.99	2.19
	3) Upstream Left	6.12	2.35
	4) Downstream	2.28	2.51
	5) 18" Downstream Rt	5.24	2.51
	6) 18" Downstream Center	3.92	2.73
	7) 18" Downstream Left		
Rock 2	1) Upstream Center	4.07	2.51
	2) Upstream Rt	5.28	2.49
	3) Upstream Left	4.90	1.78
	4) Downstream	1.01	2.14
	5) 18" Downstream Rt	4.76	2.89
	6) 18" Downstream Center	1.46	2.37
	7) 18" Downstream Left	3.97	1.80
Rock 1	1) Upstream Center	4.39	2.41
	2) Upstream Rt	5.45	1.95
	3) Upstream Left	4.79	2.58
	4) Downstream	1.03	2.07
	5) 18" Downstream Rt	4.88	1.68
	6) 18" Downstream Center	2.63	1.90
	7) 18" Downstream Left	6.27	2.60

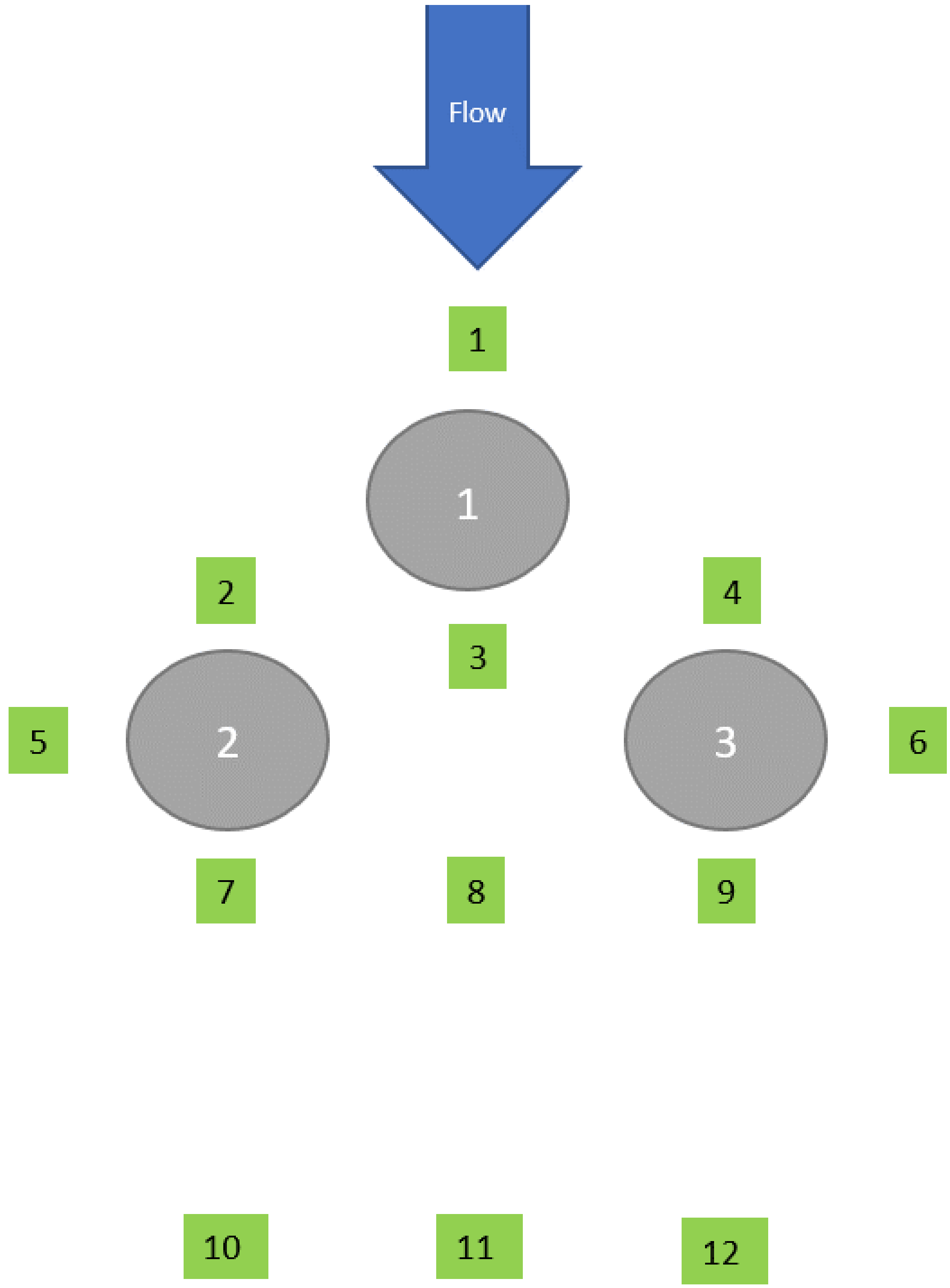

Figure D 2. Location of ADV measurements taken for an Upstream "V" configuration

Table D 6. ADV results for Upstream "V" configuration at the low density (2 clusters, 6 rocks) at 300cfs.

Upstream "V" ADV: 300cfs Low Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	5.12	1.59
	18ft Center	4.75	1.71
	18ft Left	4.05	1.73
	23ft Rt	6.08	1.35
	30ft Rt	5.49	1.34
	30ft Center	4.96	1.92
	30ft Left	2.37	1.44
	36ft Rt	4.24	1.82
Cluster 4	1) Upstream of Center Rock (Rock 4)	1.64	1.93
	2) Upstream Center Right Rock (Rock 6)	2.97	2.65
	3) Downstream of Center Rock (Rock 4)	1.14	1.98
	4) Upstream Center Left Rock (Rock 15)	0.11	1.44
	5) Rightmost Point (Rock 6)	6.30	2.44
	6) Leftmost point (Rock 15)	2.80	0.80
	7) Downstream Center Right Rock (Rock 6)	0.53	1.80
	8) Second Downstream of Center Rock (Rock 4)	5.00	1.80
	9) Downstream Center Left Rock (Rock 15)	0.38	1.15
	10) 18" Downstream Rt	2.16	1.86
	11) 18" Downstream Center	4.45	1.47
	12) 18" Downstream Left	1.07	1.22
Cluster 2	1) Upstream of Center Rock (Rock 2)	2.09	1.85
	2) Upstream Center Right Rock (Rock 11)	4.54	1.73
	3) Downstream of Center Rock (Rock 2)	1.66	1.42
	4) Upstream Center Left Rock (Rock 12)	3.77	0.97
	5) Rightmost Point (Rock 11)	6.84	2.06
	6) Leftmost Point (Rock 12)	0.09	0.94
	7) Downstream Center Right Rock (Rock 11)	0.23	1.57
	8) Second Downstream of Center Rock (Rock 2)	4.68	1.34
	9) Downstream Center Left Rock (Rock 12)	0.10	0.94
	10) 18" Downstream Rt	0.09	1.59
	11) 18" Downstream Center	4.62	1.68
	12) 18" Downstream Left	2.06	1.30

Table D 7. ADV results for Upstream “V” configuration at the low density (2 clusters, 6 rocks) at 600cfs.

Upstream "V" ADV: 600cfs Low Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	5.40	1.85
	18ft Center Rt	5.15	2.64
	18ft Center Left	5.66	2.23
	18ft Left	3.72	1.60
	23ft Rt	5.92	1.55
	23ft Center Rt	5.88	2.53
	30ft Rt	5.70	1.98
	30ft Center Rt	6.43	2.97
	30ft Center Left	3.89	2.49
	30ft Left	2.63	1.82
	36ft Rt	5.57	1.64
	36ft Center Rt	6.48	2.97
Cluster 4	1) Upstream of Center Rock (Rock 4)	2.73	2.70
	2) Upstream Center Right Rock (Rock 6)	3.49	3.11
	3) Downstream of Center Rock (Rock 4)	1.93	2.69
	4) Upstream Center Left Rock (Rock 15)	2.38	2.01
	5) Rightmost Point (Rock 6)	7.09	2.98
	6) Leftmost point (Rock 15)	3.48	1.05
	7) Downstream Center Right Rock (Rock 6)	2.67	2.55
	8) Second Downstream of Center Rock (Rock 4)	5.69	2.48
	9) Downstream Center Left Rock (Rock 15)	1.99	1.85
	10) 18" Downstream Rt	2.50	2.57
	11) 18" Downstream Center	5.30	2.44
	12) 18" Downstream Left	1.73	1.85
Cluster 2	1) Upstream of Center Rock (Rock 2)	3.64	2.30
	2) Upstream Center Right Rock (Rock 11)	5.68	2.24
	3) Downstream of Center Rock (Rock 2)	3.25	1.82
	4) Upstream Center Left Rock (Rock 12)	4.75	1.69
	5) Rightmost Point (Rock 11)	6.62	2.32
	6) Leftmost Point (Rock 12)	4.80	1.15
	7) Downstream Center Right Rock (Rock 11)	2.57	2.09
	8) Second Downstream of Center Rock (Rock 2)	4.60	1.95

9) Downstream Center Left Rock (Rock 12)	1.18	1.93
10) 18" Downstream Rt	2.03	2.19
11) 18" Downstream Center	4.64	2.20
12) 18" Downstream Left	2.24	1.60

Table D 8. ADV results for Upstream "V" configuration at the medium density (3 clusters, 9 rocks) at 300cfs.

Upstream "V" ADV: 300cfs Medium Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	4.59	1.63
Baseline	18ft Center	4.57	1.71
Baseline	18ft Left	3.61	1.73
Baseline	23ft Rt	4.77	1.52
Baseline	30ft Left	3.45	1.74
Baseline	36ft Rt	3.44	2.34
Cluster 4	1) Upstream of Center Rock (Rock 4)	2.53	2.18
Cluster 4	2) Upstream Center Right Rock (Rock 6)	3.36	2.53
Cluster 4	3) Downstream of Center Rock (Rock 4)	1.36	1.68
Cluster 4	4) Upstream Center Left Rock (Rock 15)	0.15	1.59
Cluster 4	5) Rightmost Point (Rock 6)	5.20	2.16
Cluster 4	6) Leftmost point (Rock 15)	2.76	0.70
Cluster 4	7) Downstream Center Right Rock (Rock 6)	0.36	2.03
Cluster 4	8) Second Downstream of Center Rock (Rock 4)	6.33	1.86
Cluster 4	9) Downstream Center Left Rock (Rock 15)	0.81	0.92
Cluster 4	10) 18" Downstream Rt	0.70	2.30
Cluster 4	11) 18" Downstream Center	3.80	1.38
Cluster 4	12) 18" Downstream Left	1.40	0.97
Cluster 3	1) Upstream of Center Rock (Rock 3)	3.38	2.35
Cluster 3	2) Upstream Center Right Rock (Rock 7)	3.35	2.24
Cluster 3	3) Downstream of Center Rock (Rock 3)	2.79	1.61
Cluster 3	4) Upstream Center Left Rock (Rock 5)	4.54	2.44
Cluster 3	5) Rightmost Point (Rock 7)	5.54	2.28
Cluster 3	6) Leftmost point (Rock 5)	4.34	2.16
Cluster 3	7) Downstream Center Right Rock (Rock 7)	0.80	1.63
Cluster 3	8) Second Downstream of Center Rock (Rock 3)	6.55	1.99
Cluster 3	9) Downstream Center Left Rock (Rock 5)	0.62	2.01
Cluster 3	10) 18" Downstream Rt	0.19	1.95
Cluster 3	11) 18" Downstream Center	2.37	1.90
Cluster 3	12) 18" Downstream Left	0.77	2.57
Cluster 2	1) Upstream of Center Rock (Rock 2)	1.89	1.94
Cluster 2	2) Upstream Center Right Rock (Rock 11)	4.05	2.02
Cluster 2	3) Downstream of Center Rock (Rock 2)	1.11	1.50

4) Upstream Center Left Rock (Rock 12)	3.67	1.23
5) Rightmost Point (Rock 11)	5.19	2.24
6) Leftmost Point (Rock 12)	0.27	0.96
7) Downstream Center Right Rock (Rock 11)	0.64	1.95
8) Second Downstream of Center Rock (Rock 2)	3.89	1.48
9) Downstream Center Left Rock (Rock 12)	0.29	1.18
10) 18" Downstream Rt	0.65	1.99
11) 18" Downstream Center	3.47	1.61
12) 18" Downstream Left	0.39	1.38

Table D 9. ADV results for Upstream “V” configuration at the medium density (3 clusters, 9 rocks) at 600cfs.

Upstream "V" ADV: 600cfs Medium Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	5.07	1.95
	18ft Center Rt	5.11	2.31
	18ft Center Left	5.09	2.19
	18ft Left	3.26	1.60
	23ft Rt	5.51	1.76
	23ft Center Rt	5.15	2.35
	30ft Rt	5.81	2.20
	30ft Left	3.45	1.98
	36ft Rt	6.42	1.68
	36ft Center Rt	4.07	2.94
Cluster 4	1) Upstream of Center Rock (Rock 4)	3.68	2.77
	2) Upstream Center Right Rock (Rock 6)	3.33	3.40
	3) Downstream of Center Rock (Rock 4)	2.04	2.65
	4) Upstream Center Left Rock (Rock 15)	5.44	2.11
	5) Rightmost Point (Rock 6)	5.36	2.89
	6) Leftmost point (Rock 15)	4.14	1.10
	7) Downstream Center Right Rock (Rock 6)	2.13	2.57
	8) Second Downstream of Center Rock (Rock 4)	5.13	2.60
	9) Downstream Center Left Rock (Rock 15)	2.16	1.92
	10) 18" Downstream Rt	2.09	2.66
	11) 18" Downstream Center	5.30	2.32
	12) 18" Downstream Left	3.22	1.88
Cluster 3	1) Upstream of Center Rock (Rock 3)	4.69	2.93
	2) Upstream Center Right Rock (Rock 7)	4.60	2.82
	3) Downstream of Center Rock (Rock 3)	2.57	2.20
	4) Upstream Center Left Rock (Rock 5)	3.74	2.86
	5) Rightmost Point (Rock 7)	5.94	2.69
	6) Leftmost point (Rock 5)	5.21	2.58
	7) Downstream Center Right Rock (Rock 7)	2.88	2.11
	8) Second Downstream of Center Rock (Rock 3)	7.66	2.44
	9) Downstream Center Left Rock (Rock 5)	2.43	2.58
	10) 18" Downstream Rt	0.63	2.45
	11) 18" Downstream Center	5.71	2.56
	12) 18" Downstream Left	2.61	2.90

Cluster 2	1) Upstream of Center Rock (Rock 2)	4.11	2.66
	2) Upstream Center Right Rock (Rock 11)	5.06	2.53
	3) Downstream of Center Rock (Rock 2)	3.84	2.20
	4) Upstream Center Left Rock (Rock 12)	4.92	1.59
	5) Rightmost Point (Rock 11)	5.84	2.64
	6) Leftmost Point (Rock 12)	3.26	1.60
	7) Downstream Center Right Rock (Rock 11)	2.64	2.35
	8) Second Downstream of Center Rock (Rock 2)	4.88	1.86
	9) Downstream Center Left Rock (Rock 12)	1.12	1.77
	10) 18" Downstream Rt	1.41	2.39
	11) 18" Downstream Center	4.75	2.10
	12) 18" Downstream Left	1.49	1.80

Table D 10. ADV results for Upstream "V" configuration at the high density (4 clusters, 12 rocks) at 300cfs.

Upstream "V" ADV: 300cfs High Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	3.28	2.02
	18ft Center	3.36	2.07
	18ft Left	3.25	1.82
	30ft Left	3.99	1.81
	36ft Rt	5.08	1.92
Cluster 4	1) Upstream of Center Rock (Rock 4)	3.10	2.22
	2) Upstream Center Right Rock (Rock 6)	3.63	2.52
	3) Downstream of Center Rock (Rock 4)	1.43	1.98
	4) Upstream Center Left Rock (Rock 15)	3.63	1.47
	5) Rightmost Point (Rock 6)	5.47	2.34
	6) Leftmost point (Rock 15)	0.14	0.89
	7) Downstream Center Right Rock (Rock 6)	0.43	1.88
	8) Second Downstream of Center Rock (Rock 4)	5.68	2.05
	9) Downstream Center Left Rock (Rock 15)	0.40	1.17
	10) 18" Downstream Rt	1.56	1.90
	11) 18" Downstream Center	4.25	1.39
	12) 18" Downstream Left	1.10	1.04
Cluster 3	1) Upstream of Center Rock (Rock 3)	1.75	2.53
	2) Upstream Center Right Rock (Rock 7)	4.18	2.24
	3) Downstream of Center Rock (Rock 3)	4.87	1.80
	4) Upstream Center Left Rock (Rock 5)	2.97	2.26
	5) Rightmost Point (Rock 7)	4.84	2.24
	6) Leftmost point (Rock 5)	4.35	1.94
	7) Downstream Center Right Rock (Rock 7)	0.56	1.69
	8) Second Downstream of Center Rock (Rock 3)	3.02	2.19
	9) Downstream Center Left Rock (Rock 5)	0.27	1.99
	10) 18" Downstream Rt	0.71	1.90
	11) 18" Downstream Center	1.80	1.99
	12) 18" Downstream Left	0.67	2.14
Cluster 2	1) Upstream of Center Rock (Rock 2)	2.87	2.26
	2) Upstream Center Right Rock (Rock 11)	4.48	1.93
	3) Downstream of Center Rock (Rock 2)	0.86	1.71
	4) Upstream Center Left Rock (Rock 12)	4.69	1.23

	5) Rightmost Point (Rock 11)	6.91	2.11
	6) Leftmost Point (Rock 12)	6.84	1.17
	7) Downstream Center Right Rock (Rock 11)	0.64	1.88
	8) Second Downstream of Center Rock (Rock 2)	4.22	1.64
	9) Downstream Center Left Rock (Rock 12)	0.52	1.26
	10) 18" Downstream Rt	1.18	1.85
	11) 18" Downstream Center	3.21	1.82
	12) 18" Downstream Left	0.13	1.63
Cluster 1	1) Upstream of Center Rock (Rock 1)	2.57	2.10
	2) Upstream Center Right Rock (Rock 8)	2.26	1.60
	3) Downstream of Center Rock (Rock 1)	1.21	1.60
	4) Upstream Center Left Rock (Rock 9)	3.74	2.01
	5) Rightmost Point (Rock 8)		
	6) Leftmost point (Rock 9)	4.75	1.95
	7) Downstream Center Right Rock (Rock 8)	0.49	1.18
	8) Second Downstream of Center Rock (Rock 1)	4.54	1.99
	9) Downstream Center Left Rock (Rock 9)	1.92	2.11
	10) 18" Downstream Rt	0.69	1.19
	11) 18" Downstream Center	4.30	1.86
	12) 18" Downstream Left	1.30	1.64

Table D 11. ADV results for Upstream “V” configuration at the high density (4 clusters, 12 rocks) at 600cfs.

Upstream "V" ADV: 600cfs High Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	3.66	2.24
	18ft Center Rt	3.85	2.58
	18ft Center Left	3.87	2.66
	18ft Left	3.88	2.09
	30ft Rt	4.83	2.30
	30ft Left	3.88	2.13
	36ft Rt	5.61	1.86
	36ft Center Rt	3.86	2.86
Cluster 4	1) Upstream of Center Rock (Rock 4)	4.72	2.79
	2) Upstream Center Right Rock (Rock 6)	3.77	3.21
	3) Downstream of Center Rock (Rock 4)	3.37	2.30
	4) Upstream Center Left Rock (Rock 15)	4.37	2.18
	5) Rightmost Point (Rock 6)	5.53	2.82
	6) Leftmost point (Rock 15)	4.45	1.15
	7) Downstream Center Right Rock (Rock 6)	2.19	2.64
	8) Second Downstream of Center Rock (Rock 4)	7.01	1.97
	9) Downstream Center Left Rock (Rock 15)	3.21	1.85
	10) 18" Downstream Rt	2.34	2.90
	11) 18" Downstream Center	6.62	2.23
	12) 18" Downstream Left	3.97	2.01
Cluster 3	1) Upstream of Center Rock (Rock 3)	4.94	2.98
	2) Upstream Center Right Rock (Rock 7)	4.43	2.83
	3) Downstream of Center Rock (Rock 3)	4.67	2.23
	4) Upstream Center Left Rock (Rock 5)	2.97	2.89
	5) Rightmost Point (Rock 7)	5.25	2.55
	6) Leftmost point (Rock 5)	5.11	2.62
	7) Downstream Center Right Rock (Rock 7)	0.99	2.07
	8) Second Downstream of Center Rock (Rock 3)	7.46	2.55
	9) Downstream Center Left Rock (Rock 5)	2.92	2.35
	10) 18" Downstream Rt	1.15	2.47
	11) 18" Downstream Center	4.99	2.61
	12) 18" Downstream Left	3.05	2.72
Clu	1) Upstream of Center Rock (Rock 2)	3.66	2.79

	2) Upstream Center Right Rock (Rock 11)	5.12	2.66
	3) Downstream of Center Rock (Rock 2)	6.34	1.94
	4) Upstream Center Left Rock (Rock 12)	5.56	1.76
	5) Rightmost Point (Rock 11)	7.67	2.19
	6) Leftmost Point (Rock 12)	5.44	1.73
	7) Downstream Center Right Rock (Rock 11)	2.94	2.26
	8) Second Downstream of Center Rock (Rock 2)	4.78	2.32
	9) Downstream Center Left Rock (Rock 12)	2.05	1.85
	10) 18" Downstream Rt	0.71	2.55
	11) 18" Downstream Center	4.64	2.41
	12) 18" Downstream Left	3.15	2.14
	1) Upstream of Center Rock (Rock 1)	3.80	2.66
	2) Upstream Center Right Rock (Rock 8)	3.03	2.94
	3) Downstream of Center Rock (Rock 1)	3.12	2.53
	4) Upstream Center Left Rock (Rock 9)	4.55	2.06
	5) Rightmost Point (Rock 8)		
Cluster 1	6) Leftmost point (Rock 9)	6.34	2.68
	7) Downstream Center Right Rock (Rock 8)	0.35	1.52
	8) Second Downstream of Center Rock (Rock 1)	5.74	2.16
	9) Downstream Center Left Rock (Rock 9)	0.60	2.18
	10) 18" Downstream Rt	0.74	1.90
	11) 18" Downstream Center	5.41	2.15
	12) 18" Downstream Left	0.79	2.27

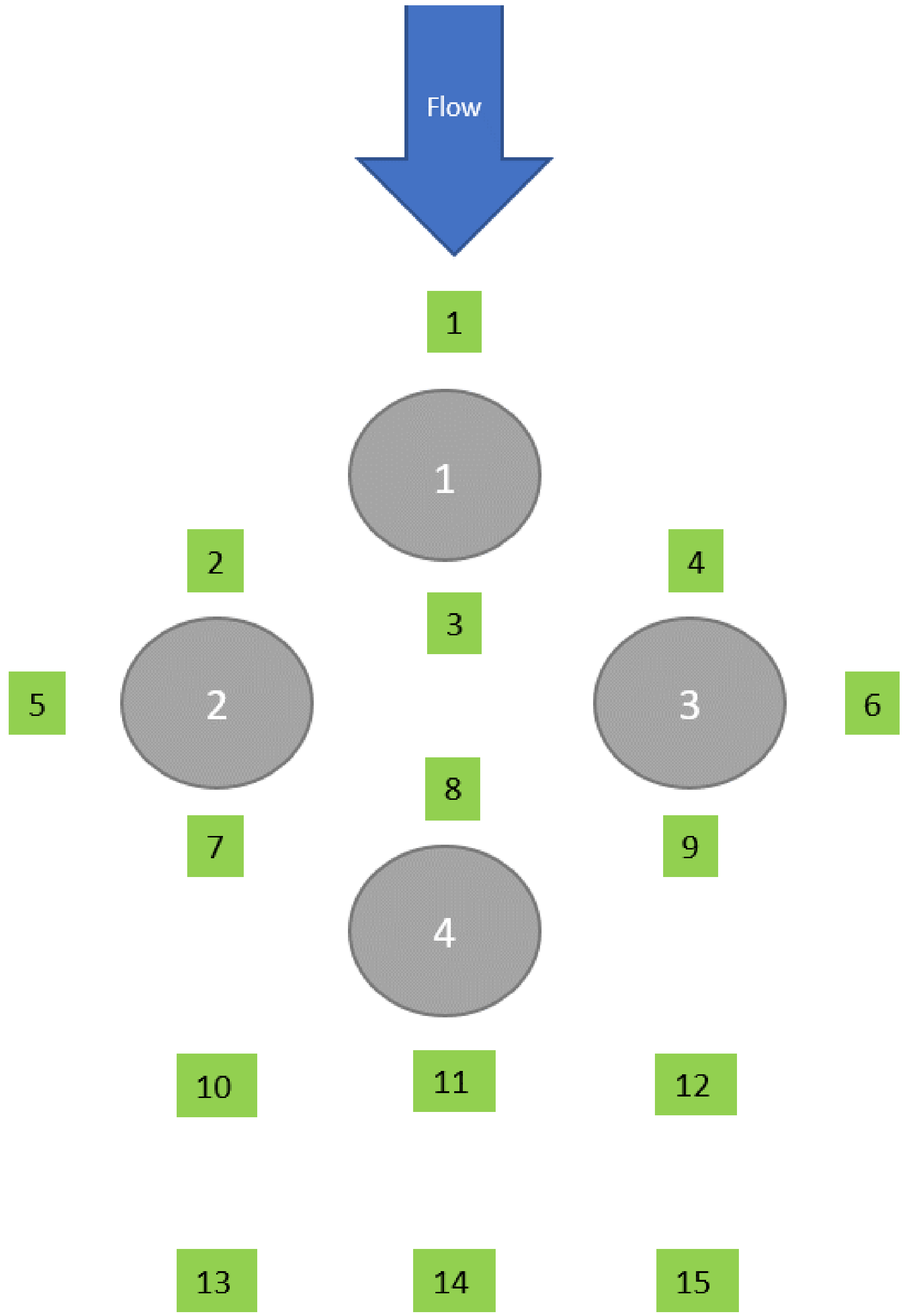

Figure D 3. Location of ADV measurements taken for a diamond configuration

Table D 12. ADV results for Diamond configuration at the low density (2 clusters, 8 rocks) at 300cfs.

Diamond ADV: 300cfs Low Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	4.73	1.63
	18ft Center	4.42	1.55
	18ft Left	3.90	1.51
	23ft Rt	5.22	1.54
	30ft Rt	5.33	1.56
	30ft Center	4.75	1.92
	30ft Left	2.37	1.59
	36 Rt	4.17	1.86
Cluster 4	1) Upstream of Center Rock (Rock 4)	1.58	1.89
	2) Upstream of Rightmost Rock	5.63	2.66
	3) Downstream of Upper Center Rock (Rock 4)	3.36	2.16
	4) Upstream of Left Rock (Rock 15)	1.37	1.60
	5) Rightmost Point (Rock 6)	3.17	2.34
	6) Leftmost Point (Rock 15)	2.69	0.76
	7) Downstream of Right Rock (Rock 6)	1.34	2.39
	8) Upstream of Lower Center Rock (Rock 16)	1.18	2.13
	9) Downstream of Left Rock (Rock 15)	1.88	1.04
	10) Downstream Rt of Lower Center Rock (Rock 16)	3.95	1.92
	11) Downstream of Lower Center Rock (Rock 16)	0.14	1.48
	12) Downstream Left of Lower Center Rock (Rock 16)	3.12	1.21
	13) 18" Downstream Rt (Rock 16)	4.44	1.85
	14) 18" Downstream Center (Rock 16)	0.76	1.99
	15) 18" Downstream Left (Rock 16)	3.67	0.94
Cluster 2	1) Upstream of Center Rock (Rock 2)	1.94	1.93
	2) Upstream of Rightmost Rock (Rock 11)	5.91	2.05
	3) Downstream of Upper Center Rock (Rock 2)	0.75	1.46
	4) Upstream of Left Rock (Rock 12)	0.04	1.14
	5) Rightmost Point (Rock 11)	4.19	1.84
	6) Leftmost Point (Rock 12)	4.14	0.97
	7) Downstream of Right Rock (Rock 11)	2.43	1.52
	8) Upstream of Lower Center Rock (Rock 13)	3.69	1.36
	9) Downstream of Left Rock (Rock 12)	1.88	0.96
	10) Downstream Rt of Lower Center Rock (Rock 13)	4.04	1.60
	11) Downstream of Lower Center Rock (Rock 13)	0.17	1.54
	12) Downstream Left of Lower Center Rock (Rock 13)	2.37	0.91

13) 18" Downstream Rt (Rock 13)	2.55	1.76
14) 18" Downstream Center (Rock 13)	0.31	1.25
15) 18" Downstream Left (Rock 13)	2.49	1.08

Table D 13. ADV results for Diamond configuration at the low density (2 clusters, 8 rocks) at 600cfs.

Diamond ADV: 600cfs Low Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	5.23	1.86
	18ft Center Rt	4.86	2.58
	18ft Center Left	5.17	2.26
	18ft Left	4.00	1.73
	23ft Rt	6.17	1.63
	23ft Center Rt	5.64	2.07
	30ft Rt	5.30	1.86
	30ft Center Rt	6.21	2.90
	30ft Center Left	3.44	2.73
	30 Left	3.25	1.74
	36ft Rt	5.46	1.61
	36ft Center Rt	6.33	3.00
Cluster 4	1) Upstream of Center Rock (Rock 4)	2.26	2.57
	2) Upstream of Rightmost Rock	3.75	3.24
	3) Downstream of Upper Center Rock (Rock 4)	4.42	2.55
	4) Upstream of Left Rock (Rock 15)	3.86	2.15
	5) Rightmost Point (Rock 6)	7.22	3.06
	6) Leftmost Point (Rock 15)	3.44	1.10
	7) Downstream of Right Rock (Rock 6)	2.23	2.57
	8) Upstream of Lower Center Rock (Rock 16)	0.69	2.45
	9) Downstream of Left Rock (Rock 15)	2.03	1.63
	10) Downstream Rt of Lower Center Rock (Rock 16)	3.52	2.65
	11) Downstream of Lower Center Rock (Rock 16)	0.36	2.36
	12) Downstream Left of Lower Center Rock (Rock 16)	3.44	1.65
	13) 18" Downstream Rt (Rock 16)	4.33	2.68
	14) 18" Downstream Center (Rock 16)	1.12	2.52
	15) 18" Downstream Left (Rock 16)	3.63	1.90
Cluster 2	1) Upstream of Center Rock (Rock 2)	3.46	2.41
	2) Upstream of Rightmost Rock (Rock 11)	6.57	2.34
	3) Downstream of Upper Center Rock (Rock 2)	3.50	2.03
	4) Upstream of Left Rock (Rock 12)	5.13	1.51
	5) Rightmost Point (Rock 11)	5.70	2.74
	6) Leftmost Point (Rock 12)	4.42	1.13
	7) Downstream of Right Rock (Rock 11)	2.53	2.19

8) Upstream of Lower Center Rock (Rock 13)	3.05	2.51
9) Downstream of Left Rock (Rock 12)	4.77	1.51
10) Downstream Rt of Lower Center Rock (Rock 13)	4.96	2.13
11) Downstream of Lower Center Rock (Rock 13)	0.44	1.92
12) Downstream Left of Lower Center Rock (Rock 13)	4.53	1.48
13) 18" Downstream Rt (Rock 13)	3.58	2.09
14) 18" Downstream Center (Rock 13)	0.26	1.77
15) 18" Downstream Left (Rock 13)	3.79	1.63

Table D 14. ADV results for Diamond configuration at the medium density (3 clusters, 12 rocks) at 300cfs.

Diamond ADV: 300cfs Medium Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	4.22	1.72
	18ft Center	4.46	1.73
	18ft Left	3.98	1.68
	23 Rt	4.39	1.61
	30 Left	3.36	1.81
	36 Rt	5.42	2.26
Cluster 4	1) Upstream of Center Rock (Rock 4)	2.60	2.30
	2) Upstream of Rightmost Rock	4.84	2.64
	3) Downstream of Upper Center Rock (Rock 4)	3.37	1.76
	4) Upstream of Left Rock (Rock 15)	0.17	1.64
	5) Rightmost Point (Rock 6)	3.56	2.37
	6) Leftmost Point (Rock 15)	3.50	0.75
	7) Downstream of Right Rock (Rock 6)	1.54	2.05
	8) Upstream of Lower Center Rock (Rock 16)	0.89	2.14
	9) Downstream of Left Rock (Rock 15)	0.15	1.14
	10) Downstream Rt of Lower Center Rock (Rock 16)	4.55	1.93
	11) Downstream of Lower Center Rock (Rock 16)	0.35	1.54
	12) Downstream Left of Lower Center Rock (Rock 16)	1.67	1.17
	13) 18" Downstream Rt (Rock 16)	3.18	1.82
	14) 18" Downstream Center (Rock 16)	1.17	1.81
	15) 18" Downstream Left (Rock 16)	3.56	0.94
Cluster 3	1) Upstream of Center Rock (Rock 3)	2.66	2.37
	2) Upstream of Rightmost Rock (Rock 7)	4.74	2.24
	3) Downstream of Upper Center Rock (Rock 3)	2.06	2.16
	4) Upstream of Left Rock (Rock 5)	4.32	2.15
	5) Rightmost Point (Rock 7)	3.49	2.19
	6) Leftmost Point (Rock 5)	3.75	2.05
	7) Downstream of Right Rock (Rock 7)	0.70	1.73
	8) Upstream of Lower Center Rock (Rock 14)	3.55	1.92
	9) Downstream of Left Rock (Rock 5)	0.43	1.89
	10) Downstream Rt of Lower Center Rock (Rock 14)	4.74	2.01
	11) Downstream of Lower Center Rock (Rock 14)	0.35	2.06
	12) Downstream Left of Lower Center Rock (Rock 14)	3.50	2.20
	13) 18" Downstream Rt (Rock 14)	3.32	2.18
	14) 18" Downstream Center (Rock 14)	0.28	2.16

	15) 18" Downstream Left (Rock 14)	3.57	2.20
Cluster 2	1) Upstream of Center Rock (Rock 2)	2.00	1.88
	2) Upstream of Rightmost Rock (Rock 11)	5.21	1.84
	3) Downstream of Upper Center Rock (Rock 2)	0.90	1.82
	4) Upstream of Left Rock (Rock 12)	3.90	1.19
	5) Rightmost Point (Rock 11)	3.40	1.94
	6) Leftmost Point (Rock 12)	3.70	0.84
	7) Downstream of Right Rock (Rock 11)	1.37	1.89
	8) Upstream of Lower Center Rock (Rock 13)	2.93	1.48
	9) Downstream of Left Rock (Rock 12)	0.78	1.33
	10) Downstream Rt of Lower Center Rock (Rock 13)	2.75	1.94
	11) Downstream of Lower Center Rock (Rock 13)	0.62	1.61
	12) Downstream Left of Lower Center Rock (Rock 13)	2.06	1.19
	13) 18" Downstream Rt (Rock 13)	1.68	1.90
	14) 18" Downstream Center (Rock 13)	0.30	1.86
	15) 18" Downstream Left (Rock 13)	1.55	1.40

Table D 15. ADV results for Diamond configuration at the medium density (3 clusters, 12 rocks) at 600cfs.

Diamond ADV: 600cfs Medium Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	5.28	1.95
	18ft Center Rt	5.96	2.69
	18ft Center Left	5.40	2.20
	18ft Left	3.52	1.81
	23 Rt	5.58	1.76
	23 Center Rt	5.68	2.43
	30 Rt	5.63	2.27
	30 Left	3.18	2.34
	36 Rt	6.20	1.69
	36 Center Rt	4.41	3.00
Cluster 4	1) Upstream of Center Rock (Rock 4)	3.64	2.79
	2) Upstream of Rightmost Rock	4.75	3.23
	3) Downstream of Upper Center Rock (Rock 4)	3.49	2.37
	4) Upstream of Left Rock (Rock 15)	4.26	2.18
	5) Rightmost Point (Rock 6)	3.85	2.90
	6) Leftmost Point (Rock 15)	4.15	1.43
	7) Downstream of Right Rock (Rock 6)	2.34	2.82
	8) Upstream of Lower Center Rock (Rock 16)	1.90	2.74
	9) Downstream of Left Rock (Rock 15)	2.80	1.90
	10) Downstream Rt of Lower Center Rock (Rock 16)	3.24	2.82
	11) Downstream of Lower Center Rock (Rock 16)	0.64	2.32
	12) Downstream Left of Lower Center Rock (Rock 16)	2.85	1.80
	13) 18" Downstream Rt (Rock 16)	4.18	2.83
	14) 18" Downstream Center (Rock 16)	2.69	2.72
	15) 18" Downstream Left (Rock 16)	4.09	1.61
Cluster 3	1) Upstream of Center Rock (Rock 3)	4.49	3.00
	2) Upstream of Rightmost Rock (Rock 7)	5.79	3.04
	3) Downstream of Upper Center Rock (Rock 3)	4.51	2.58
	4) Upstream of Left Rock (Rock 5)	5.21	2.82
	5) Rightmost Point (Rock 7)	4.55	2.62
	6) Leftmost Point (Rock 5)	4.01	2.91
	7) Downstream of Right Rock (Rock 7)	1.42	2.09
	8) Upstream of Lower Center Rock (Rock 14)	6.02	2.70

	9) Downstream of Left Rock (Rock 5)	3.72	2.72
	10) Downstream Rt of Lower Center Rock (Rock 14)	5.40	2.82
	11) Downstream of Lower Center Rock (Rock 14)	0.54	2.57
	12) Downstream Left of Lower Center Rock (Rock 14)	4.00	2.82
	13) 18" Downstream Rt (Rock 14)	4.54	2.69
	14) 18" Downstream Center (Rock 14)	0.32	3.21
	15) 18" Downstream Left (Rock 14)	4.08	2.68
Cluster 2	1) Upstream of Center Rock (Rock 2)	2.31	2.27
	2) Upstream of Rightmost Rock (Rock 11)	3.61	2.53
	3) Downstream of Upper Center Rock (Rock 2)	2.93	1.95
	4) Upstream of Left Rock (Rock 12)	0.55	1.95
	5) Rightmost Point (Rock 11)	5.71	2.40
	6) Leftmost Point (Rock 12)	4.69	1.25
	7) Downstream of Right Rock (Rock 11)	5.10	2.36
	8) Upstream of Lower Center Rock (Rock 13)	3.77	2.61
	9) Downstream of Left Rock (Rock 12)	4.92	1.94
	10) Downstream Rt of Lower Center Rock (Rock 13)	3.66	2.66
	11) Downstream of Lower Center Rock (Rock 13)	3.44	2.39
	12) Downstream Left of Lower Center Rock (Rock 13)	3.42	1.81
	13) 18" Downstream Rt (Rock 13)	0.57	0.01
	14) 18" Downstream Center (Rock 13)	3.07	2.03
	15) 18" Downstream Left (Rock 13)	4.09	1.99

Table D 16. ADV results for Diamond configuration at the high density (4 clusters, 16 rocks) at 300cfs.

Diamond ADV: 300cfs High Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	3.65	1.95
	18ft Center	3.46	1.98
	18ft Left	2.93	1.72
	30 Left	3.00	1.82
	36 Rt	5.07	2.19
Cluster 4	1) Upstream of Center Rock (Rock 4)	3.28	2.20
	2) Upstream of Rightmost Rock (Rock 6)	3.85	2.62
	3) Downstream of Upper Center Rock (Rock 4)	1.34	2.06
	4) Upstream of Left Rock (Rock 15)	3.76	1.72
	5) Rightmost Point (Rock 6)	5.07	2.26
	6) Leftmost Point (Rock 15)	0.54	0.68
	7) Downstream of Right Rock (Rock 6)	0.82	2.28
	8) Upstream of Lower Center Rock (Rock 16)	3.48	2.10
	9) Downstream of Left Rock (Rock 15)	0.16	0.87
	10) Downstream Rt of Lower Center Rock (Rock 16)	5.18	1.92
	11) Downstream of Lower Center Rock (Rock 16)	1.18	1.34
	12) Downstream Left of Lower Center Rock (Rock 16)		
	13) 18" Downstream Rt (Rock 16)	3.70	1.88
	14) 18" Downstream Center (Rock 16)	1.09	1.72
	15) 18" Downstream Left (Rock 16)		
Cluster 3	1) Upstream of Center Rock (Rock 3)	2.94	2.52
	2) Upstream of Rightmost Rock (Rock 7)	4.50	2.36
	3) Downstream of Upper Center Rock (Rock 3)	1.97	2.35
	4) Upstream of Left Rock (Rock 5)	3.66	2.82
	5) Rightmost Point (Rock 7)	5.05	2.34
	6) Leftmost Point (Rock 5)	4.36	1.99
	7) Downstream of Right Rock (Rock 7)	0.84	1.51
	8) Upstream of Lower Center Rock (Rock 14)	5.43	1.98
	9) Downstream of Left Rock (Rock 5)	0.28	1.92
	10) Downstream Rt of Lower Center Rock (Rock 14)	2.69	2.05
	11) Downstream of Lower Center Rock (Rock 14)	0.38	2.23
	12) Downstream Left of Lower Center Rock (Rock 14)	2.67	2.36
	13) 18" Downstream Rt (Rock 14)	3.07	2.39
	14) 18" Downstream Center (Rock 14)	0.87	2.05

	15) 18" Downstream Left (Rock 14)	4.40	2.07
Cluster 2	1) Upstream of Center Rock (Rock 2)	2.83	2.26
	2) Upstream of Rightmost Rock (Rock 11)	4.14	2.18
	3) Downstream of Upper Center Rock (Rock 2)	1.49	1.89
	4) Upstream of Left Rock (Rock 12)	4.53	1.44
	5) Rightmost Point (Rock 11)	6.38	2.34
	6) Leftmost Point (Rock 12)	4.84	1.99
	7) Downstream of Right Rock (Rock 11)	1.76	1.92
	8) Upstream of Lower Center Rock (Rock 13)	3.21	1.72
	9) Downstream of Left Rock (Rock 12)	0.92	1.46
	10) Downstream Rt of Lower Center Rock (Rock 13)	2.71	2.01
	11) Downstream of Lower Center Rock (Rock 13)	0.26	1.99
	12) Downstream Left of Lower Center Rock (Rock 13)	1.71	1.35
	13) 18" Downstream Rt (Rock 13)	0.78	1.89
	14) 18" Downstream Center (Rock 13)	0.22	1.60
	15) 18" Downstream Left (Rock 13)	1.80	1.68
Cluster 1	1) Upstream of Center Rock (Rock 1)	2.42	2.09
	2) Upstream of Rightmost Rock (Rock 8)	2.16	1.59
	3) Downstream of Upper Center Rock (Rock 1)	1.16	2.03
	4) Upstream of Left Rock (Rock 9)	3.34	1.99
	5) Rightmost Point (Rock 8)		
	6) Leftmost Point (Rock 9)	4.61	2.06
	7) Downstream of Right Rock (Rock 8)	1.03	1.14
	8) Upstream of Lower Center Rock (Rock 10)	2.42	1.97
	9) Downstream of Left Rock (Rock 9)	1.98	1.92
	10) Downstream Rt of Lower Center Rock (Rock 10)	2.63	1.35
	11) Downstream of Lower Center Rock (Rock 10)	0.28	1.63
	12) Downstream Left of Lower Center Rock (Rock 10)	2.50	1.63
	13) 18" Downstream Rt (Rock 10)	2.44	1.13
	14) 18" Downstream Center (Rock 10)	0.86	1.65
	15) 18" Downstream Left (Rock 10)	4.23	1.98

Table D 17. ADV results for Diamond configuration at the high density (4 clusters, 16 rocks) at 600cfs.

Diamond ADV: 600cfs High Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	3.72	2.60
	18ft Center Rt	3.66	2.83
	18ft Center Left	4.07	2.73
	18ft Left	3.94	1.93
	30 Rt	3.62	2.13
	30 Left	3.41	1.95
	36 Rt	5.41	2.20
	36 Center Rt	4.11	2.94
Cluster 4	1) Upstream of Center Rock (Rock 4)	4.07	2.81
	2) Upstream of Rightmost Rock	4.69	3.23
	3) Downstream of Upper Center Rock (Rock 4)	6.20	2.28
	4) Upstream of Left Rock (Rock 15)	4.28	2.14
	5) Rightmost Point (Rock 6)	3.86	3.23
	6) Leftmost Point (Rock 15)	5.56	1.33
	7) Downstream of Right Rock (Rock 6)	2.30	2.60
	8) Upstream of Lower Center Rock (Rock 16)	2.14	2.60
	9) Downstream of Left Rock (Rock 15)	3.80	1.86
	10) Downstream Rt of Lower Center Rock (Rock 16)	3.26	2.94
	11) Downstream of Lower Center Rock (Rock 16)	1.29	2.48
	12) Downstream Left of Lower Center Rock (Rock 16)	3.87	1.88
	13) 18" Downstream Rt (Rock 16)	4.11	2.73
	14) 18" Downstream Center (Rock 16)	1.10	2.58
	15) 18" Downstream Left (Rock 16)	4.59	1.64
Cluster 3	1) Upstream of Center Rock (Rock 3)	4.68	2.97
	2) Upstream of Rightmost Rock (Rock 7)	5.17	3.06
	3) Downstream of Upper Center Rock (Rock 3)	3.67	2.61
	4) Upstream of Left Rock (Rock 5)	4.04	3.20
	5) Rightmost Point (Rock 7)	5.26	2.62
	6) Leftmost Point (Rock 5)	4.81	2.60
	7) Downstream of Right Rock (Rock 7)	1.46	2.03
	8) Upstream of Lower Center Rock (Rock 14)	6.55	2.35
	9) Downstream of Left Rock (Rock 5)	3.97	2.61
	10) Downstream Rt of Lower Center Rock (Rock 14)	3.21	2.78
	11) Downstream of Lower Center Rock (Rock 14)	0.35	2.61

	12) Downstream Left of Lower Center Rock (Rock 14)	4.09	2.74
	13) 18" Downstream Rt (Rock 14)	3.62	2.77
	14) 18" Downstream Center (Rock 14)	1.09	2.97
	15) 18" Downstream Left (Rock 14)	4.37	2.70
Cluster 2	1) Upstream of Center Rock (Rock 2)	3.63	2.94
	2) Upstream of Rightmost Rock (Rock 11)	4.84	2.83
	3) Downstream of Upper Center Rock (Rock 2)	3.32	1.86
	4) Upstream of Left Rock (Rock 12)	5.18	1.93
	5) Rightmost Point (Rock 11)	4.48	2.35
	6) Leftmost Point (Rock 12)	5.60	1.97
	7) Downstream of Right Rock (Rock 11)	3.59	2.37
	8) Upstream of Lower Center Rock (Rock 13)	2.65	2.34
	9) Downstream of Left Rock (Rock 12)	4.37	2.27
	10) Downstream Rt of Lower Center Rock (Rock 13)	5.37	2.66
	11) Downstream of Lower Center Rock (Rock 13)	1.01	2.28
	12) Downstream Left of Lower Center Rock (Rock 13)	5.51	1.93
	13) 18" Downstream Rt (Rock 13)	4.51	2.58
	14) 18" Downstream Center (Rock 13)	0.42	2.39
	15) 18" Downstream Left (Rock 13)	3.87	1.84
Cluster 1	1) Upstream of Center Rock (Rock 1)	3.05	2.79
	2) Upstream of Rightmost Rock (Rock 8)	2.71	2.79
	3) Downstream of Upper Center Rock (Rock 1)	3.27	2.37
	4) Upstream of Left Rock (Rock 9)	5.61	2.51
	5) Rightmost Point (Rock 8)		
	6) Leftmost Point (Rock 9)	4.09	2.60
	7) Downstream of Right Rock (Rock 8)	1.39	1.59
	8) Upstream of Lower Center Rock (Rock 10)	3.76	2.45
	9) Downstream of Left Rock (Rock 9)	5.47	2.73
	10) Downstream Rt of Lower Center Rock (Rock 10)	2.76	1.85
	11) Downstream of Lower Center Rock (Rock 10)	0.49	2.23
	12) Downstream Left of Lower Center Rock (Rock 10)	3.86	2.24
	13) 18" Downstream Rt (Rock 10)	3.18	1.68
	14) 18" Downstream Center (Rock 10)	1.36	2.15
	15) 18" Downstream Left (Rock 10)	4.54	2.44

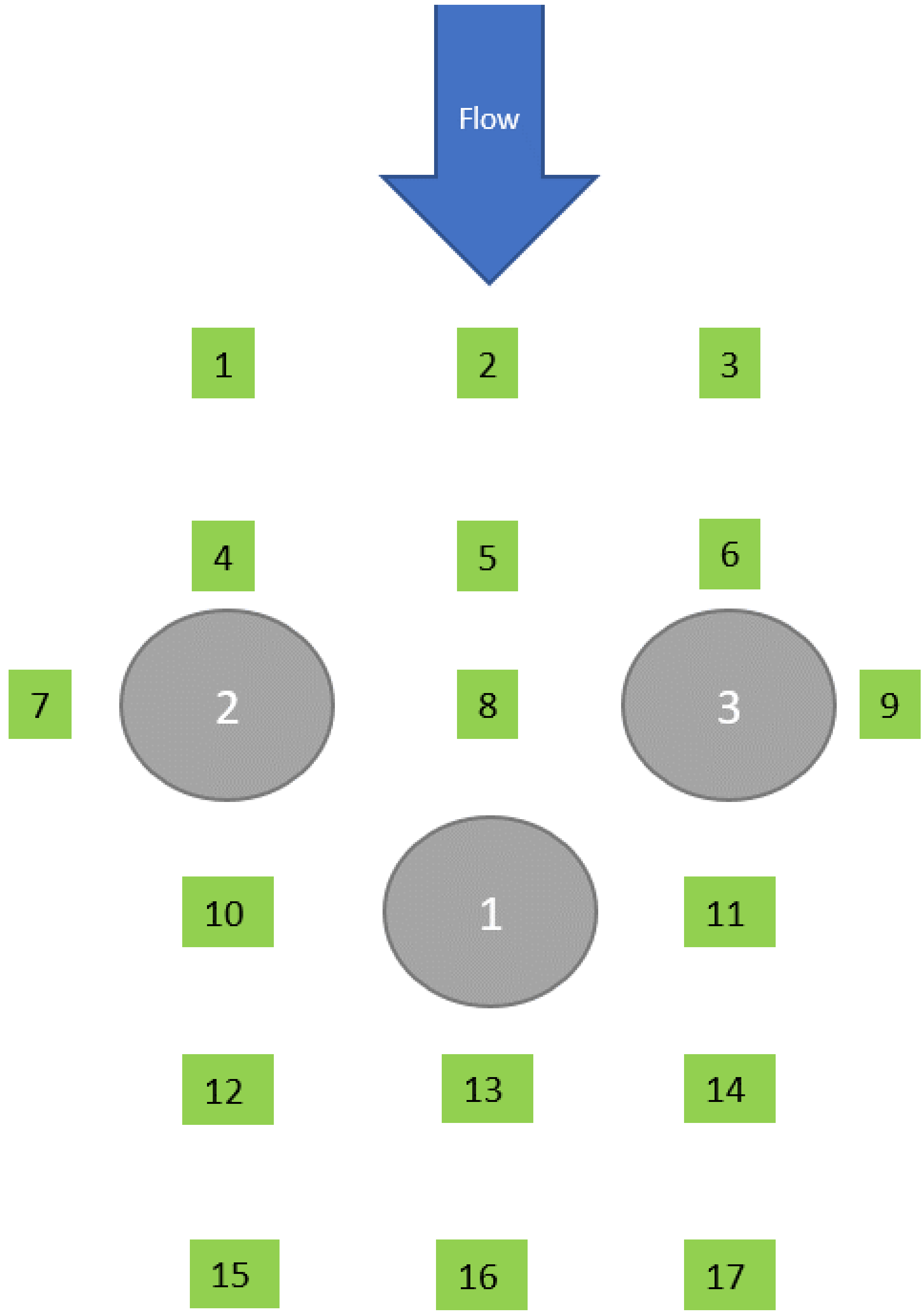

Figure D 4. Location of ADV measurements taken for a Downstream "V" configuration

Table D 18. ADV results for Downstream "V" configuration at the low density (2 clusters, 6 rocks) at 300cfs.

Downstream "V" ADV: 300cfs Low Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	4.98	1.57
	18ft Center	4.66	1.57
	18ft Left	3.23	1.33
	23ft Rt	5.90	1.60
	23ft Center	6.65	1.61
	30ft Rt	4.12	1.71
	30ft Center	4.77	1.85
	30ft Left	2.43	1.76
	36ft Rt	5.11	1.61
Cluster 4	1) 18" US Rt	3.51	2.10
	2) 18" US Center	1.74	2.07
	3) 18" US Left	1.68	1.57
	4) US Center of Rt Rock (Rock 6)	2.68	2.56
	5) US Upper Center of Lower Rock (Rock 4)	1.39	1.90
	6) US Center of Left Rock (Rock 15)	1.41	1.56
	7) Rightmost Point (Rock 6)	5.34	2.40
	8) US Lower Center of Lower Rock (Rock 4)	4.62	1.78
	9) Leftmost Point (Rock 15)	0.98	0.76
	10) DS Center of Rt Rock (Rock 6)	0.92	1.94
	11) DS Center of Left Rock (Rock 15)	1.87	0.91
	12) Lower Rock DS Rt (Rock 4)	3.35	1.77
	13) Lower Rock DS Center (Rock 4)	0.33	1.33
	14) Lower Rock DS Left (Rock 4)	2.95	1.31
	15) 18" DS Rt (Rock 4)	2.60	2.05
	16) 18" DS Center (Rock 4)	2.37	1.51
	17) 18" DS Left (Rock 4)	4.07	1.02
Cluster 2	1) 18" US Rt	3.19	1.80
	2) 18" US Center	3.27	1.55
	3) 18" US Left	2.62	1.29
	4) US Center of Rt Rock (Rock 11)	2.76	2.03
	5) US Upper Center of Lower Rock (Rock 2)	2.74	1.89
	6) US Center of Left Rock (Rock 12)	1.46	1.39
	7) Rightmost Point	5.80	1.80
	8) US Lower Center of Lower Rock (Rock 2)	4.22	1.61
	9) Leftmost Point (Rock 12)	2.07	0.80

10) DS Center of Rt Rock (Rock 11)	1.43	1.09
11) DS Center of Left Rock (Rock 12)	0.84	1.08
12) Lower Rock DS Rt (Rock 2)	6.05	1.55
13) Lower Rock DS Center (Rock 2)	0.45	1.04
14) Lower Rock DS Left (Rock 2)	4.78	1.19
15) 18" DS Rt (Rock 2)	4.42	1.48
16) 18" DS Center (Rock 2)	1.32	1.10
17) 18" DS Left (Rock 2)	4.13	0.87

Table D 19. ADV results for Downstream "V" configuration at the low density (2 clusters, 6 rocks) at 600cfs.

Downstream "V" ADV: 600cfs Low Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	4.66	1.90
	18ft Center Rt	5.20	2.37
	18ft Center Left	4.79	2.34
	18ft Left	4.26	1.80
	23ft Rt	6.04	1.61
	23ft Center Rt	7.53	2.22
	30ft Rt	6.57	1.81
	30ft Center Rt	6.39	2.61
	30ft Center Left	3.94	2.73
	30 Left	2.81	0.13
	36ft Rt	5.97	1.68
	36ft Center Rt	7.60	2.73
Cluster 4	1) 18" US Rt	4.06	2.69
	2) 18" US Center	2.66	2.44
	3) 18" US Left	2.84	1.94
	4) US Center of Rt Rock (Rock 6)	3.31	3.08
	5) US Upper Center of Lower Rock (Rock 4)	2.41	2.55
	6) US Center of Left Rock (Rock 15)	1.81	2.13
	7) Rightmost Point (Rock 6)	5.85	3.08
	8) US Lower Center of Lower Rock (Rock 4)	4.64	2.24
	9) Leftmost Point (Rock 15)	3.71	1.38
	10) DS Center of Rt Rock (Rock 6)	2.94	2.57
	11) DS Center of Left Rock (Rock 15)	2.03	1.73
	12) Lower Rock DS Rt (Rock 4)	4.00	2.44
	13) Lower Rock DS Center (Rock 4)	0.73	1.95
	14) Lower Rock DS Left (Rock 4)	4.58	1.71
	15) 18" DS Rt (Rock 4)	3.77	2.57
	16) 18" DS Center (Rock 4)	0.84	2.16
	17) 18" DS Left (Rock 4)	3.80	1.64
Cluster 2	1) 18" US Rt	3.99	2.37
	2) 18" US Center	4.54	2.18
	3) 18" US Left	2.92	1.78
	4) US Center of Rt Rock (Rock 11)	3.96	2.73
	5) US Upper Center of Lower Rock (Rock 2)	3.99	2.51
	6) US Center of Left Rock (Rock 12)	2.92	1.82

7) Rightmost Point	5.91	2.22
8) US Lower Center of Lower Rock (Rock 2)	5.09	1.52
9) Leftmost Point (Rock 12)	4.10	1.22
10) DS Center of Rt Rock (Rock 11)	7.24	1.82
11) DS Center of Left Rock (Rock 12)	4.18	1.68
12) Lower Rock DS Rt (Rock 2)	7.39	1.94
13) Lower Rock DS Center (Rock 2)	2.09	1.52
14) Lower Rock DS Left (Rock 2)	6.73	1.61
15) 18" DS Rt (Rock 2)	5.18	2.07
16) 18" DS Center (Rock 2)	0.25	2.02
17) 18" DS Left (Rock 2)	6.52	1.46

Table D 20. ADV results for Downstream "V" configuration at the medium density (3 clusters, 9 rocks) at 300cfs.

Downstream "V" ADV: 300cfs Medium Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	4.33	1.67
	18ft Center	4.67	1.92
	18ft Left	3.84	1.52
	23ft Rt	4.77	1.73
	23ft Center	4.74	1.80
	30ft Left	4.04	2.02
	36ft Rt	5.99	1.69
Cluster 4	1) 18" US Rt	3.66	2.11
	2) 18" US Center	3.82	2.19
	3) 18" US Left	3.88	1.78
	4) US Center of Rt Rock (Rock 6)	3.13	2.34
	5) US Upper Center of Lower Rock (Rock 4)	2.73	2.13
	6) US Center of Left Rock (Rock 15)	3.20	1.76
	7) Rightmost Point (Rock 6)	4.36	2.47
	8) US Lower Center of Lower Rock (Rock 4)	5.00	2.23
	9) Leftmost Point (Rock 15)	0.20	0.80
	10) DS Center of Rt Rock (Rock 6)	1.01	2.06
	11) DS Center of Left Rock (Rock 15)	1.42	1.00
	12) Lower Rock DS Rt (Rock 4)	4.32	1.93
	13) Lower Rock DS Center (Rock 4)	0.26	1.40
	14) Lower Rock DS Left (Rock 4)	4.02	1.17
	15) 18" DS Rt (Rock 4)	2.46	1.81
	16) 18" DS Center (Rock 4)	2.33	1.61
	17) 18" DS Left (Rock 4)	3.29	1.02
Cluster 3	1) 18" US Rt	4.48	1.89
	2) 18" US Center	4.62	1.92
	3) 18" US Left	3.10	2.23
	4) US Center of Rt Rock (Rock 7)	2.47	2.15
	5) US Upper Center of Lower Rock (Rock 3)	3.90	2.58
	6) US Center of Left Rock (Rock 5)	2.98	2.47
	7) Rightmost Point (Rock 7)	5.38	1.69
	8) US Lower Center of Lower Rock (Rock 3)	5.30	2.48
	9) Leftmost Point (Rock 5)	5.18	1.90
	10) DS Center of Rt Rock (Rock 7)	1.82	1.67
	11) DS Center of Left Rock (Rock 5)	3.73	2.15

	12) Lower Rock DS Rt (Rock 3)	3.48	2.09
	13) Lower Rock DS Center (Rock 3)	0.32	2.32
	14) Lower Rock DS Left (Rock 3)	4.19	2.07
	15) 18" DS Rt (Rock 3)	4.08	1.72
	16) 18" DS Center (Rock 3)	0.25	2.06
	17) 18" DS Left (Rock 3)	2.99	1.94
Cluster 2	1) 18" US Rt	2.95	1.86
	2) 18" US Center	3.46	1.73
	3) 18" US Left	2.15	1.31
	4) US Center of Rt Rock (Rock 11)	2.04	2.11
	5) US Upper Center of Lower Rock (Rock 2)	2.59	1.84
	6) US Center of Left Rock (Rock 12)	1.70	1.60
	7) Rightmost Point	5.04	1.81
	8) US Lower Center of Lower Rock (Rock 2)	3.75	1.72
	9) Leftmost Point (Rock 12)	2.98	0.83
	10) DS Center of Rt Rock (Rock 11)	1.19	1.86
	11) DS Center of Left Rock (Rock 12)	1.60	1.36
	12) Lower Rock DS Rt (Rock 2)	5.38	1.74
	13) Lower Rock DS Center (Rock 2)	0.26	1.68
	14) Lower Rock DS Left (Rock 2)	3.71	1.43
	15) 18" DS Rt (Rock 2)	2.39	1.73
	16) 18" DS Center (Rock 2)	0.35	1.63
	17) 18" DS Left (Rock 2)	3.19	1.12

Table D 21. ADV results for Downstream “V” configuration at the medium density (3 clusters, 9 rocks) at 600cfs.

Downstream "V" ADV: 600cfs Medium Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Rt	4.69	1.86
	18ft Center Rt	5.14	2.74
	18ft Center Left	5.17	2.65
	18ft Left	3.14	1.80
	23 Rt	5.54	1.81
	23 Center Rt	6.32	2.10
	30 Rt	6.00	1.85
	30 Left	4.06	1.65
	36 Rt	6.85	1.85
	36 Center Rt	5.89	2.99
Cluster 4	1) 18" US Rt	4.75	2.87
	2) 18" US Center	3.71	2.83
	3) 18" US Left	3.96	2.24
	4) US Center of Rt Rock (Rock 6)	3.77	3.03
	5) US Upper Center of Lower Rock (Rock 4)	3.34	2.90
	6) US Center of Left Rock (Rock 15)	3.38	2.19
	7) Rightmost Point (Rock 6)	5.19	2.90
	8) US Lower Center of Lower Rock (Rock 4)	5.42	2.40
	9) Leftmost Point (Rock 15)	4.91	1.51
	10) DS Center of Rt Rock (Rock 6)	6.52	2.62
	11) DS Center of Left Rock (Rock 15)	3.85	1.95
	12) Lower Rock DS Rt (Rock 4)	5.77	2.53
	13) Lower Rock DS Center (Rock 4)	0.54	2.26
	14) Lower Rock DS Left (Rock 4)	4.52	1.80
	15) 18" DS Rt (Rock 4)	4.32	2.85
	16) 18" DS Center (Rock 4)	1.78	2.53
	17) 18" DS Left (Rock 4)	4.22	2.24
Cluster 3	1) 18" US Rt	4.94	2.49
	2) 18" US Center	5.28	2.61
	3) 18" US Left	4.29	2.87
	4) US Center of Rt Rock (Rock 7)	4.69	2.70
	5) US Upper Center of Lower Rock (Rock 3)	5.01	2.89
	6) US Center of Left Rock (Rock 5)	3.66	2.81
	7) Rightmost Point (Rock 7)	5.82	2.48

	8) US Lower Center of Lower Rock (Rock 3)	6.31	2.85
	9) Leftmost Point (Rock 5)	4.65	2.40
	10) DS Center of Rt Rock (Rock 7)	4.18	2.44
	11) DS Center of Left Rock (Rock 5)	6.35	2.79
	12) Lower Rock DS Rt (Rock 3)	4.38	2.22
	13) Lower Rock DS Center (Rock 3)	0.84	2.53
	14) Lower Rock DS Left (Rock 3)	5.85	2.68
	15) 18" DS Rt (Rock 3)	4.97	2.81
	16) 18" DS Center (Rock 3)	1.63	2.44
	17) 18" DS Left (Rock 3)	5.11	2.82
Cluster 2	1) 18" US Rt	4.46	2.64
	2) 18" US Center	4.20	2.30
	3) 18" US Left	3.44	1.78
	4) US Center of Rt Rock (Rock 11)	4.12	2.60
	5) US Upper Center of Lower Rock (Rock 2)	3.47	2.32
	6) US Center of Left Rock (Rock 12)	3.19	2.20
	7) Rightmost Point	5.41	2.64
	8) US Lower Center of Lower Rock (Rock 2)	4.78	2.48
	9) Leftmost Point (Rock 12)	3.43	1.34
	10) DS Center of Rt Rock (Rock 11)	6.58	2.01
	11) DS Center of Left Rock (Rock 12)	3.21	1.61
	12) Lower Rock DS Rt (Rock 2)	6.78	2.26
	13) Lower Rock DS Center (Rock 2)	2.34	1.97
	14) Lower Rock DS Left (Rock 2)	5.52	1.86
	15) 18" DS Rt (Rock 2)	3.63	2.44
	16) 18" DS Center (Rock 2)	0.99	2.31
	17) 18" DS Left (Rock 2)	4.69	1.71

Table D 22. ADV results for Downstream "V" configuration at the high density (4 clusters, 12 rocks) at 300cfs.

Downstream "V" ADV: 300cfs High Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Left	3.78	1.81
	23ft Rt	3.14	2.02
	23ft Center	6.49	2.02
	30ft Left	4.02	1.76
	36ft Rt	6.15	1.65
Cluster 4	1) 18" US Rt	4.21	2.27
	2) 18" US Center	4.19	2.06
	3) 18" US Left	3.67	1.29
	4) US Center of Rt Rock (Rock 6)	2.70	2.39
	5) US Upper Center of Lower Rock (Rock 4)	3.28	2.13
	6) US Center of Left Rock (Rock 15)	3.44	1.72
	7) Rightmost Point (Rock 6)	5.04	2.32
	8) US Lower Center of Lower Rock (Rock 4)	4.65	2.13
	9) Leftmost Point (Rock 15)	1.83	0.96
	10) DS Center of Rt Rock (Rock 6)	1.83	1.76
	11) DS Center of Left Rock (Rock 15)	0.38	1.18
	12) Lower Rock DS Rt (Rock 4)	4.25	1.69
	13) Lower Rock DS Center (Rock 4)	0.41	1.57
	14) Lower Rock DS Left (Rock 4)	3.96	1.18
	15) 18" DS Rt (Rock 4)	2.15	1.94
	16) 18" DS Center (Rock 4)	2.19	1.74
	17) 18" DS Left (Rock 4)	3.70	0.96
Cluster 3	1) 18" US Rt	4.19	1.98
	2) 18" US Center	4.73	2.30
	3) 18" US Left	3.05	2.20
	4) US Center of Rt Rock (Rock 7)	2.31	2.55
	5) US Upper Center of Lower Rock (Rock 3)	4.57	2.05
	6) US Center of Left Rock (Rock 5)	3.02	2.55
	7) Rightmost Point (Rock 7)	4.56	1.69
	8) US Lower Center of Lower Rock (Rock 3)	5.75	2.11
	9) Leftmost Point (Rock 5)	4.31	1.76
	10) DS Center of Rt Rock (Rock 7)	1.45	1.59
	11) DS Center of Left Rock (Rock 5)	3.91	2.11
	12) Lower Rock DS Rt (Rock 3)	2.78	2.37

	13) Lower Rock DS Center (Rock 3)	0.77	2.11
	14) Lower Rock DS Left (Rock 3)	4.32	2.13
	15) 18" DS Rt (Rock 3)	4.33	1.77
	16) 18" DS Center (Rock 3)	0.13	2.07
	17) 18" DS Left (Rock 3)	3.08	2.01
	1) 18" US Rt	3.78	2.06
	2) 18" US Center	3.74	1.80
	3) 18" US Left	2.76	1.55
	4) US Center of Rt Rock (Rock 11)	2.90	2.23
	5) US Upper Center of Lower Rock (Rock 2)	3.16	2.44
	6) US Center of Left Rock (Rock 12)	1.95	1.80
	7) Rightmost Point	6.32	1.72
Cluster 2	8) US Lower Center of Lower Rock (Rock 2)	4.31	1.54
	9) Leftmost Point (Rock 12)	4.28	1.01
	10) DS Center of Rt Rock (Rock 11)	1.98	1.60
	11) DS Center of Left Rock (Rock 12)	0.82	1.18
	12) Lower Rock DS Rt (Rock 2)	3.54	1.69
	13) Lower Rock DS Center (Rock 2)	0.25	1.30
	14) Lower Rock DS Left (Rock 2)	4.58	1.67
	15) 18" DS Rt (Rock 2)	0.81	1.85
	16) 18" DS Center (Rock 2)	2.12	1.31
	17) 18" DS Left (Rock 2)	4.46	1.26
	1) 18" US Rt	2.23	1.54
	2) 18" US Center	3.16	2.27
	3) 18" US Left	2.40	2.13
	4) US Center of Right Rock (Rock 8)	1.53	1.92
	5) US Upper Center of Lower Rock (Rock 1)	3.12	1.81
	6) US Center of Left Rock (Rock 9)	2.18	2.07
	7) Rightmost Point (Rock 8)		
Cluster 1	8) US Lower Center of Lower Rock (Rock 1)	3.96	1.89
	9) Leftmost Point (Rock 9)	4.15	2.26
	10) DS Center of Right Rock (Rock 8)	3.57	1.35
	11) DS Center of Left Rock (Rock 9)	1.86	1.98
	12) Lower Rock DS Rt (Rock 1)	3.07	1.33
	13) Lower Rock DS Center (Rock 1)	0.29	1.73
	14) Lower Rock DS Left (Rock 1)	3.78	1.88
	15) 18" DS Rt (Rock 1)	3.57	1.17
	16) 18" DS Center (Rock 1)	0.66	1.65
	17) 18" DS Left (Rock 1)	3.80	1.97

Table D 23. ADV results for Downstream "V" configuration at the high density (4 clusters, 12 rocks) at 600cfs.

Downstream "V" ADV: 600cfs High Density

	Location	Prototype Velocity ft/s	Prototype Depth ft
Baseline	18ft Center Left	4.60	2.78
	18ft Left	4.56	1.95
	23ft Rt	3.87	1.80
	23ft Center Rt	5.48	2.62
	30ft Rt	5.06	1.93
	30ft Left	4.64	1.90
	36ft Rt	5.17	2.07
	36ft Center Rt	5.42	2.91
Cluster 4	1) 18" US Rt	3.79	2.83
	2) 18" US Center	3.93	2.56
	3) 18" US Left	4.55	2.14
	4) US Center of Rt Rock (Rock 6)	3.90	3.14
	5) US Upper Center of Lower Rock (Rock 4)	3.40	2.73
	6) US Center of Left Rock (Rock 15)	2.72	2.41
	7) Rightmost Point (Rock 6)	5.43	2.91
	8) US Lower Center of Lower Rock (Rock 4)	5.53	2.30
	9) Leftmost Point (Rock 15)	5.06	1.12
	10) DS Center of Rt Rock (Rock 6)	2.28	2.85
	11) DS Center of Left Rock (Rock 15)	4.09	1.77
	12) Lower Rock DS Rt (Rock 4)	6.13	2.47
	13) Lower Rock DS Center (Rock 4)	2.40	1.97
	14) Lower Rock DS Left (Rock 4)	5.01	1.81
	15) 18" DS Rt (Rock 4)	4.32	2.64
	16) 18" DS Center (Rock 4)	2.65	2.30
	17) 18" DS Left (Rock 4)	4.67	1.67
Cluster 3	1) 18" US Rt	4.77	2.48
	2) 18" US Center	5.62	2.93
	3) 18" US Left	4.29	2.87
	4) US Center of Rt Rock (Rock 7)	3.69	2.58
	5) US Upper Center of Lower Rock (Rock 3)	6.02	2.78
	6) US Center of Left Rock (Rock 5)	3.78	2.73
	7) Rightmost Point (Rock 7)	5.48	2.20
	8) US Lower Center of Lower Rock (Rock 3)	6.75	2.93
	9) Leftmost Point (Rock 5)	5.01	2.40
	10) DS Center of Rt Rock (Rock 7)	2.38	2.69

	11) DS Center of Left Rock (Rock 5)	7.26	2.72
	12) Lower Rock DS Rt (Rock 3)	3.58	2.47
	13) Lower Rock DS Center (Rock 3)	0.73	2.52
	14) Lower Rock DS Left (Rock 3)	6.11	2.39
	15) 18" DS Rt (Rock 3)	4.13	2.43
	16) 18" DS Center (Rock 3)	1.42	2.51
	17) 18" DS Left (Rock 3)	4.59	2.66
Cluster 2	1) 18" US Rt	4.80	2.64
	2) 18" US Center	5.07	2.60
	3) 18" US Left	3.84	2.26
	4) US Center of Rt Rock (Rock 11)	3.95	2.83
	5) US Upper Center of Lower Rock (Rock 2)	4.54	2.93
	6) US Center of Left Rock (Rock 12)	3.09	2.43
	7) Rightmost Point	6.95	2.58
	8) US Lower Center of Lower Rock (Rock 2)	5.46	2.43
	9) Leftmost Point (Rock 12)	4.39	1.52
	10) DS Center of Rt Rock (Rock 11)	6.69	2.26
	11) DS Center of Left Rock (Rock 12)	3.71	1.64
	12) Lower Rock DS Rt (Rock 2)	7.37	2.24
	13) Lower Rock DS Center (Rock 2)	0.38	1.88
	14) Lower Rock DS Left (Rock 2)	6.35	1.89
	15) 18" DS Rt (Rock 2)	3.14	2.32
	16) 18" DS Center (Rock 2)	1.87	2.20
	17) 18" DS Left (Rock 2)	5.29	1.84
Cluster 1	1) 18" US Rt	2.75	2.30
	2) 18" US Center	3.67	2.60
	3) 18" US Left	4.00	2.79
	4) US Center of Right Rock (Rock 8)	3.20	2.30
	5) US Upper Center of Lower Rock (Rock 1)	3.97	2.66
	6) US Center of Left Rock (Rock 9)	2.35	2.86
	7) Rightmost Point (Rock 8)		
	8) US Lower Center of Lower Rock (Rock 1)	5.02	2.60
	9) Leftmost Point (Rock 9)	5.70	2.52
	10) DS Center of Right Rock (Rock 8)	2.49	1.74
	11) DS Center of Left Rock (Rock 9)	3.07	2.41
	12) Lower Rock DS Rt (Rock 1)	4.60	1.72
	13) Lower Rock DS Center (Rock 1)	2.64	2.03
	14) Lower Rock DS Left (Rock 1)	4.99	2.30
	15) 18" DS Rt (Rock 1)	4.00	1.69
	16) 18" DS Center (Rock 1)	1.66	2.35
	17) 18" DS Left (Rock 1)	4.58	2.85