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Physical Model Testing of Boulder Cluster Configurations

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14. ABSTRACT

Large and small boulders were tested in a physical hydraulic model using Acoustic Doppler Velocimetry (ADV) and Large Scale Particle Image Velocimetry (LSPIV). For the large boulder tests, a baseline and four unique rock configurations were tested at two different flow rates. For the small boulder testing, a baseline and three unique rock configurations were tested at three different flow rates. The configurations were: Single Rock, Upstream V, Downstream V, and Diamond, where the Diamond configuration was only tested for large rocks. These configurations were tested at four to five different densities: high, medium-high (only for Single Rocks), medium, low, and very low. Water surface elevation data were collected for small boulder configurations in the streamwise direction through the test section. Dimensionless analysis was performed for boulder and flow properties to assess: 1) percent plan view area blocked; 2) percent cross-section area blocked; 3) percent volume blocked. The velocity ratios of each configuration were derived from cumulative distribution functions (CDF) for minimum, quartiles, and maximum values.

Upstream V and Downstream V boulder configurations create the greatest velocity reduction with the lowest density of boulder clusters. For all rock configurations, the more cross-sectional area obstructed by rocks, the more effectively the velocity is reduced in the channel. However, the trend does not significantly improve after 35% blocked. Therefore, the ideal amount of cross-sectional channel obstructed is between 30-40%. The higher the percent volume blocked by boulders in the modeled restoration section, the more velocity reduction was achieved for all configurations between 0 and 4% blocked. It is unclear, however, what the optimal percent blockage by volume should be, since larger percent blockages were not tested.

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Disclaimer

Cover Photo: One of the tested boulder configurations in the channel.

Funding was provided by the Bureau of Reclamation's California-Great Basin Regional Office.

Contents

Tables

Figures

Executive Summary

Boulder clusters are often used in fish passage design because they create topographic variability that produces variability in the hydraulic flow field. Boulders protrude into the flow causing a backwater effect immediately upstream and a downstream low velocity wake zone in the lee of the boulder. Boulder placement can also be useful in enhancing hydraulic variability and reducing velocities in constructed channels or in rivers with uniform conditions and a lack of low velocity habitat. The purpose of this physical model study is to quantify the velocity field associated with several different boulder configurations at different flow rates, thereby providing information on the efficacy of boulder clusters for improving fish passage and fish habitat.

Large and small boulders were tested in a physical hydraulic model using Acoustic Doppler Velocimetry (ADV) and Large Scale Particle Image Velocimetry (LSPIV). For the large boulder tests, a baseline and four unique rock configurations were tested at two different flow rates. For the small boulder testing, a baseline and three unique rock configurations were tested at three different flow rates. The configurations were: Single Rock, Upstream V, Downstream V, and Diamond, where the Diamond configuration was only tested for large rocks. These configurations were tested at four to five different densities: high, medium-high (only for Single Rocks), medium, low, and very low. Water surface elevation data were collected for small boulder configurations in the streamwise direction through the test section. Dimensionless analysis was performed for boulder and flow properties to assess: 1) percent plan view area blocked; 2) percent cross-section area blocked at the single rock or boulder cluster; 3) percent volume blocked. The velocity ratios of each configuration were derived from cumulative distribution functions (CDF) for minimum, quartiles, and maximum values. A ratio value of less than 1 means the boulder configuration was more efficient at slowing flow than at baseline where no rocks are present.

For the percent plan view area blocked in a restoration section, Upstream V and Downstream V boulder configurations create the greatest velocity reduction with the lowest density of boulder clusters. For all rock configurations, the more cross-sectional area obstructed by rocks, the more effectively the velocity is reduced in the channel. However, the trend does not significantly improve after 35%. Therefore, the ideal amount of cross-sectional channel obstructed is between 30-40%. The higher the percent volume blocked by boulders in the modeled restoration section, the more velocity reduction was achieved for all configurations between 0 and 4% blocked. It is unclear, however, what the optimal percent blockage by volume should be, since larger percent blockages were not tested.

Larger rocks performed better than smaller rocks, particularly at higher flow rates when small rocks were overtopped. A combination of small and large rocks in the Downstream and Upstream V configuration may be utilized if large rocks are not available in the required quantity. Boulder clusters placed at high density achieved the greatest velocity reduction. However, increased density will tend to raise the water surface elevation and the cost, so these factors should be considered relative to the desired velocity reduction.

Future work should focus on comparing physical model data to a 2D numerical model to see how 2D models can best simulate complex hydraulics associated with boulder clusters. Numerical models could then be used to assess project specific designs.

Introduction

Many rivers and streams have been severely impacted by anthropogenic development, channelization, hydraulic structures, and other disturbances to the natural river-floodplain environment. 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. These streams typically have declining habitat values and species diversity as flow conditions become more uniform with increased velocity. Additionally, structures such as diversion dams disrupt continuity between river segments. A healthy river system provides longitudinal, lateral, and vertical connectivity to allow for three-dimensional movement of water, nutrients, native species, and other organisms. Longitudinal connectivity is especially important for migrating fish to access upper parts of the watershed used for spawning. Constructed channels, known as nature-like fishways, are one method to provide fish passage around or through riverine structures.

Boulder clusters are often used in fish passage design because they create topographic varaibility that produces variability in the hydraulic flow field. Boulders protrude into the flow causing a backwater effect immediately upstream and a downstream low velocity wake zone in the lee of the boulder. Flow separates when approaching the boulder and accelearates around the left and right side (and over the crest if the flow depth exceeds the boulder height). The flow separation around the boulder causes a sheltered zone downstream where the velocity is reduced. This low velocity zone provides important fish habitat, especially in uniform channels where there may be limited opportunities for fish to rest.

Boulder placement can also be useful in enhancing hydraulic variability and reducing velocities in constructed channels or in rivers with uniform conditions and a lack of low velocity habitat. Boulder placement may be used to provide year-round fish habitat in locations such as constructed side channels in the Painter's Riffles on the Sacramento River near Redding, California. There is informal design guidance for placing boulder clusters (Fischenich and Seal, 2000; McCullah and Gray, 2005; Saldi-Caromile, et al., 2004; ODFW, 2010), but little quantitative information on the effect of different configuration types and densities on the velocity field. The purpose of this physical model study is to quantify the velocity field associated with several different boulder configurations at different flow rates, thereby providing information on the efficacy of boulder clusters for improving fish passage and fish habitat.

The key research questions for this study are:

1.) How do four different boulder configurations alter velocity fields to improve hydraulics for fish habitat (single rock, upstream V, downstream V, diamond)?
2.) Are large boulders required or can small boulders provide reduced velocities?
3.) Which rock placement density produces the best hydraulics for fish habitat (high, medium-high, medium, low, very low)?
4.) How does percent area blocked by boulders in plan view and cross section and percent volume blocked impact velocity?

Experimental Setup and Dimensions

Model Design

A physical hydraulic model of a river section was constructed at the Bureau of Reclamation's Hydraulics Laboratory in Denver, CO in 2018. The physical model was originally scaled to represent a low-flow channel design alternative for the Los Angeles River (Holste et. al, 2019). The model was constructed as a distorted Froude scale model using a 1:8 horizontal scale and a 1:4 vertical scale to represent prototype dimensions of 64 ft wide and about 2 ft deep. The physical model included a roughened channel bed consisting of gravel with a Manning's n value of approximately 0.039 and a sequence of two pools and riffles.

The physical model was reused for the current study with a focus on evaluating the use of boulders and boulder clusters to decrease channel velocity, provide low velocity resting areas for migrating fish, and increase hydraulic variability. Analysis in this report uses values at the laboratory scale and dimensionless terms for more generalized application to a range of site conditions. For more information on the original model design and scaling procedure please see Holste, N. and M. Shinbein (2019) "Design and Analysis of Ecosystem Features in Urban Flood Control Channels".

Model Setup

The physical hydraulic model was constructed using a template system (Figure 1) to fill the gravel bed with the pool-riffle sequence at an average slope of 0.0089 ft/ft.

Figure 1. Template system used in model construction.

Gross dimensions of the model are as follows: top width 11 ft, bottom width 3.75 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 via a rock baffle. 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 relative to the top of the banks from approximately 0.375 ft in the riffles, 0.625 ft in the pools, and has an average depth of 0.5 ft (Figure 2). A profile of the pool-riffle sequence is shown in Figure 3. A 1.5-ft-wide overflow section on either side of the compound trapezoidal was included in the model.

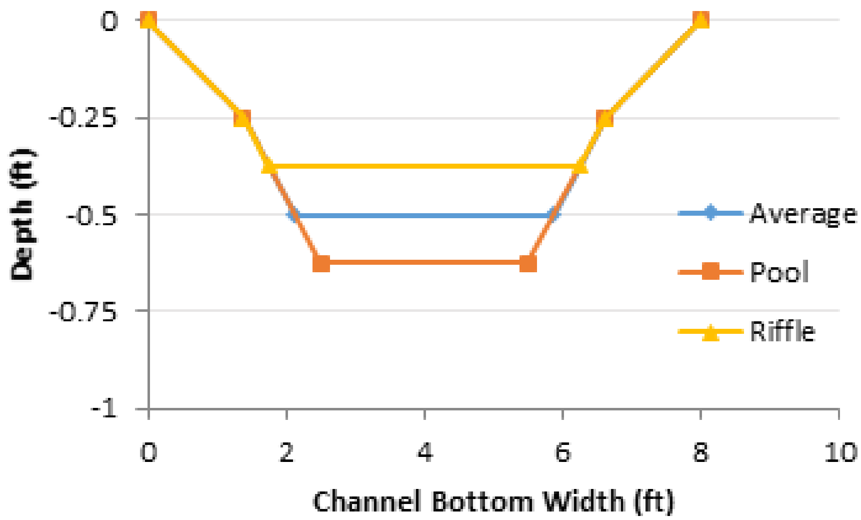

Figure 2. Cross-section of compound trapezoid channel showing pool and riffle geometry.

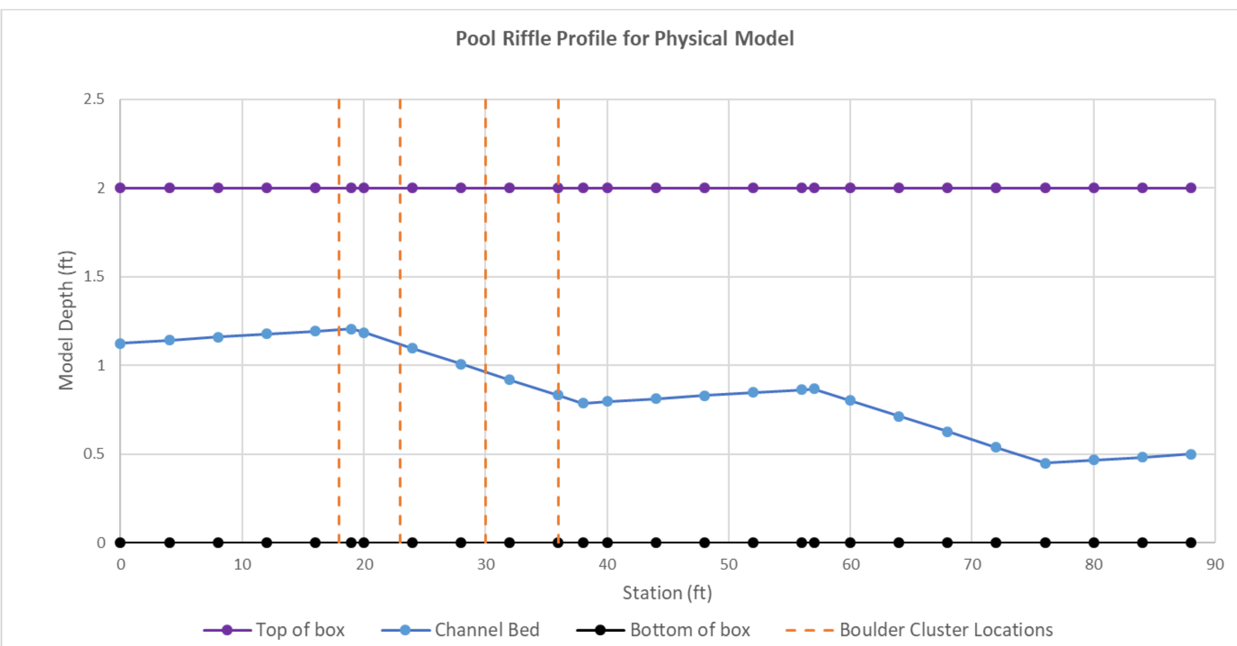

Figure 3. Pool-riffle profile along the length of the physical model.

Data Collection Methods

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 4). 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 5.

Figure 4. 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.

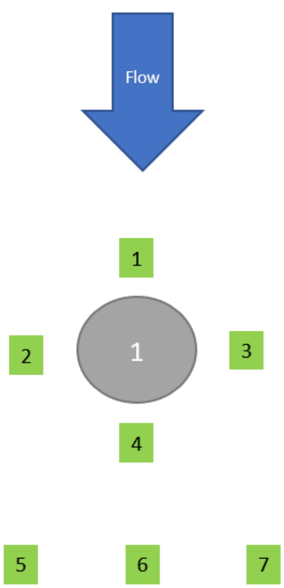

Figure 5. Example of ADV data collection locations around a single boulder.

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.

Samples were collected in Nortek's Vectrino Plus software and processed via WinADV Version 2.031 software (Wahl, 2013). Correlation values were set to 75%, but due to the shallow flow depth outside of the 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, W., & Stamhuis, E., 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 accurate or could not be measured. 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 F: Velocity Vectors and Magnitude). 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

Large and small boulders were tested during this project. Large boulders had dimensions of approximately 0.70 ft in the direction of flow (x-direction), 1.00 ft transverse to the flow (y-direction), and a height of about 0.62 ft above the bed (z-direction). Small boulders were about half the size and measured (on average) 0.55 ft in the x-direction, 0.57 ft in the y-direction, and 0.32 ft in the z-direction. For the large boulder tests, a baseline and four unique rock configurations were utilized at two different flow rates. This was adjusted slightly for the small boulder testing where a baseline and three unique rock configurations were utilized at three different flow rates (Table 1). The lowest flow rate for the small rock testing was indicative of a normal base flow in the channel. The middle flow rate for the small rocks (lowest flow for large rock testing) represents the approximate capacity of the channel before water spills out above the banks. The highest flow rate represents the maximum flow rate the physical model could reasonably pass without overtopping, which was double the channel capacity.

Table 1 Test Matrix for baseline, small rock, and large rocks.

Test	Flow Rates (cfs)	Boulder Configurations	Density	No. of Locations	No. of Boulders
Baseline	2.3, 4.7, 9.4	No Boulders	n/a	0	0
Small Rock	2.3, 4.7, 9.4	Single, Upstream “V”, Downstream “V”	Very Low to High	1-8 (Single) 1-4 (Cluster)	1-12
Large Rock	4.7, 9.4	Single, Upstream “V”, Downstream “V”, Diamond	Very Low to High	1-8 (Single) 1-4 (Cluster)	1-16

Baseline testing consisted of taking velocity readings through ADV and PIV techniques discussed in the “Data Collection Methods” section without any rocks in the channel at all flow rates. The four rock configurations were: single rock, upstream “V”, diamond, and downstream “V” for large rocks with the diamond configuration omitted in small rock testing. The configurations include single rocks and clusters, which are groupings of rocks closely together in the channel (Figure 6).

Figure 6. Single, upstream “V”, diamond, and downstream “V” configurations, respectively for the large boulder tests. For the small boulder tests only the single, upstream “V”, and downstream “V” configurations were tested.

The test matrix also included changing the density of the rock clusters, meaning the streamwise spacing of the boulder clusters within the test section. For the cluster configurations, "high density" was defined as 4 clusters, "medium density" was 3 clusters, "low density" was 2 clusters, and "very low" was one cluster. For the single rock configurations, "high density" was defined as 8 rocks, "medium-high density" was 6 rocks, "medium density" was 4 rocks, "low density" was 2 rocks, and "very low" was one rock. 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 large rocks were selected to be overtopped in the highest flow condition, but not fully submerged. All small rocks were selected to be overtopped at the middle flow condition and fully submerged at the highest flow condition. 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 A: Boulder and Flow Properties).

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 adjacent downstream 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. The single rock configuration followed this pattern with individual rocks placed in the same region.

Analysis

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 F: Velocity Vectors and Magnitude. 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.

Analysis Methods

This analysis aimed to present a generalized approach so the boulder cluster physical properties could be non-dimensional and used for more generalized application in the future. All variables used in the analysis are defined in this section.

Boulder Properties

Boulder properties describe the dimensions of boulders used in the physical model testing. As stated in Test Matrix, all large boulders were selected to be overtopped at the largest modeled discharge. All small rocks were selected to be overtopped when the trapezoidal section of the channel was full, but the upper portion of the banks were still mostly dry. Please see Appendix A: Boulder and Flow Properties for the comprehensive list of results from this analysis.

- Length for each boulder (X_B) = measured along flow direction.
- Width for each boulder (Y_B) = measured transverse to the flow direction.
- Height for each boulder (Z_B) = measured above riverbed.
- Width for each boulder cluster (Y_{BC}) = measured across widest part of the cluster.
- Average height for each boulder cluster ($\overline{Z_B}$) = the average height of the rocks comprising the cluster.
- Plan View Area for each boulder (A_{P-B}) = $X_B * Y_B$.
- Plan View Area for each boulder cluster (A_{P-BC}) = sum of A_{P-B} for each rock within the cluster.
- Plan View Area for each test configuration (A_{P-BCT}) = sum of A_{P-BC} for each cluster used in a test.
- Cross-section Area for each boulder (A_{XS-B}) = $Y_B * Z_B$
- Cross-section Area for each cluster (A_{XS-BC}) = $Y_{BC} * \overline{Z_B}$
- Cross-section Area for each test configuration (A_{XS-BCT}) = sum of A_{XS-BC} for each cluster used in a test
- Volume for each boulder (VOL_B) = $X_B * Y_B * Z_B$
- Volume for each boulder cluster (VOL_{BC}) = sum of VOL_B for each rock within the cluster
- Volume for each test (VOL_{BCT}) = sum of VOL_{BC} for each cluster used in a test

Flow Properties

Flow properties focused on the impacts the boulder(s) caused on the near-field hydraulics and overall test section. These results were assessed using the ADV data points. Please see Appendix A: Boulder and Flow Properties for the comprehensive list of results from this analysis.

- Upstream Flow Depth for each boulder or boulder cluster (Y_{US}) = the depth measurement(s) at ADV points taken immediately upstream of each boulder or boulder cluster.
  - Single rock = depth at location immediately upstream of boulder;
  - Upstream and Downstream "V" = average of depths at locations immediately upstream of each boulder in the cluster;
  - Diamond = average of depths at locations immediately upstream of each boulder in the cluster, including the downstream-most rock.
- Length of Flow Path along test section (L_x) = distance between upstream and downstream stations at bounds of test section. This was held constant throughout all tests at 26 feet.
- Length of Flow Influence downstream of each cluster (L_{Bx}) = for each cluster or single rock, the downstream distance of hydraulic influence was estimated. If there was another cluster downstream on a similar flow path, this was measured as the distance between clusters. If there was not another downstream cluster along the flow path, this was measured as the distance where the wake zone dissipates behind each boulder (the slow velocity zone tapers out, or the streamlines merge together).
- Flow Top Width at each boulder location (single rock or cluster) and at any other baseline cross-sections (W).
- Average Flow Top Width for the test section ($\overline{W}$).
- Flow Plan View Area for each test ($A_{P\text{-}Flow}$) = $L_x * \overline{W}$.
- Average Flow Depth for each test ($\overline{Y}$) = average flow depth within the test section. This was calculated using available ADV data upstream of the clusters and in the centerline for each test.
- Flow Cross-Sectional Area for each cluster or single rock ($A_{XS\text{-}Flow}$) = average flow depth at the cross-section containing the cluster or single rock (Y_{XS}) * W
- Flow Volume for each test (within the test section) (VOL_{Flow}) = $A_{P\text{-}Flow} * \overline{Y}$

Dimensionless Terms

Dimensionless variables were calculated with the goal of utilizing a percent area blocked so that results could be applied across a range of channel conditions. This would enable other channel sizes to use the dataset, as long as the percent blockage is known.

- % Plan View Area Blocked ($\%A_{P\text{-}Blocked}$) = $A_{P\text{-}BCT} / A_{P\text{-}Flow}$.
- % Cross-section Area Blocked for each cluster or single rock ($\%A_{XS\text{-}Blocked}$) = $A_{XS\text{-}BC} / A_{XS\text{-}Flow}$.
- Average % Cross-section Area Blocked for each test ($\overline{\%A_{XS-Blocked}}$) = sum of $\%A_{XS\text{-}Blocked}$ for each cluster divided by number of clusters.
- Total % Cross-section Area Blocked for each test ($\%A_{XS\text{-}Blocked\text{-}Total}$) = [sum of ($\%A_{XS\text{-}Blocked} * L_{Bx}$) for each cluster] / L_x

- Average overtopping ratio for each test ($\overline{Y_{US} / \overline{Z_B}}$) = sum of ($Y_{US}$ / $\overline{B_z}$) for each cluster divided by number of clusters.
- % Volume Blocked ($\%VOL_{Blocked}$) = VOL_{BCT} / VOL_{Flow}.

Velocity Analysis

Cumulative Distribution Function (CDF) and Probability Distribution Function (PDF) curves were generated for each configuration. The 7 ratios for velocity values were then compared for boulder results to baseline for different points along the CDF curve. The 3 ratios for velocity interquartile ranges compare the velocity variability for boulder tests to the baseline. Please see Appendix C: Velocity Distribution Curves and Appendix F: Velocity Vectors and Magnitude for the comprehensive list of results from this analysis.

- From the CDF curves:
  - V_{min} – the minimum measured velocity
  - V_{10} – the velocity where 10% is less than or equal to;
  - V_{25} – the velocity where 25% is less than or equal to;
  - V_{50} – the velocity where 50% is less than or equal to (median velocity);
  - V_{75} – the velocity where 75% is less than or equal to;
  - V_{90} – the velocity where 90% is less than or equal to;
  - V_{max} – the maximum measured velocity;
  - V_{AVG} – the average velocity for the test section;
  - SD_V – the standard deviation of the velocity distribution.
  - Interquartile ranges: (1) V_{max} and V_{min}, (2) V_{90} and V_{10}, and (3) V_{75} and V_{25}.
  - Velocity ratios comparing boulder tests to the baseline, such as: $VR_{AVG} = V_{AVG\_boulder} / V_{AVG\_baseline}$. A number less than 1 indicates the velocity at this given percentile (e.g., the median) has been reduced by the boulder configuration, a number greater than 1 indicates the velocity at this percentile has been increased by the boulder configuration.

Results

Water Surface Elevation

The water surface elevation (WSE) for all configurations was assessed for the small rocks. This profile along the length of the channel was taken at the centerline from the upstream rock baffle (described in Model Setup) to the tailboards used to control the downstream WSE. The WSE across the profile of the channel was not assessed for the large rock configurations. It should be noted that the tailboards used in the design of the model to set the downstream WSE caused some backwatering effect. This effect can be seen from approximately station 60, onwards (Figure 7 through Figure 9). The boulder configurations were all confined between Station 18 and 36. Only results for the Upstream V configuration are shown here. Please see Appendix B: Water Surface Elevations for the single rock and Downstream V profiles.

During the lowest flow rate, the small rocks for all configurations followed the trend of the baseline. The high-density configuration caused the greatest increase to WSE with an average increase of 0.03 ft. For this low flow rate, the low point at station 40 for the Upstream and Downstream V configurations was caused by drawdown from a rock immediately adjacent to this point. Even at the highest flow rate, this trend is followed. However, the Downstream V has the largest increase to WSE at the 9.4 cfs flow rate with an average increase of 0.04 ft.

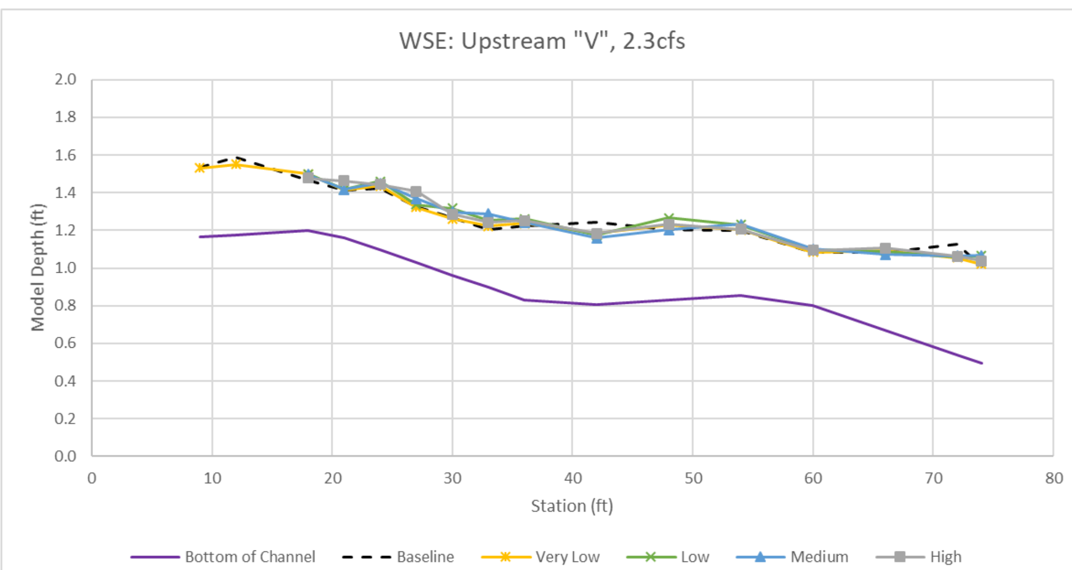

Figure 7. Water surface and channel invert profiles for small rock configurations at 2.3 cfs. Clusters were located between station 18 and 36.

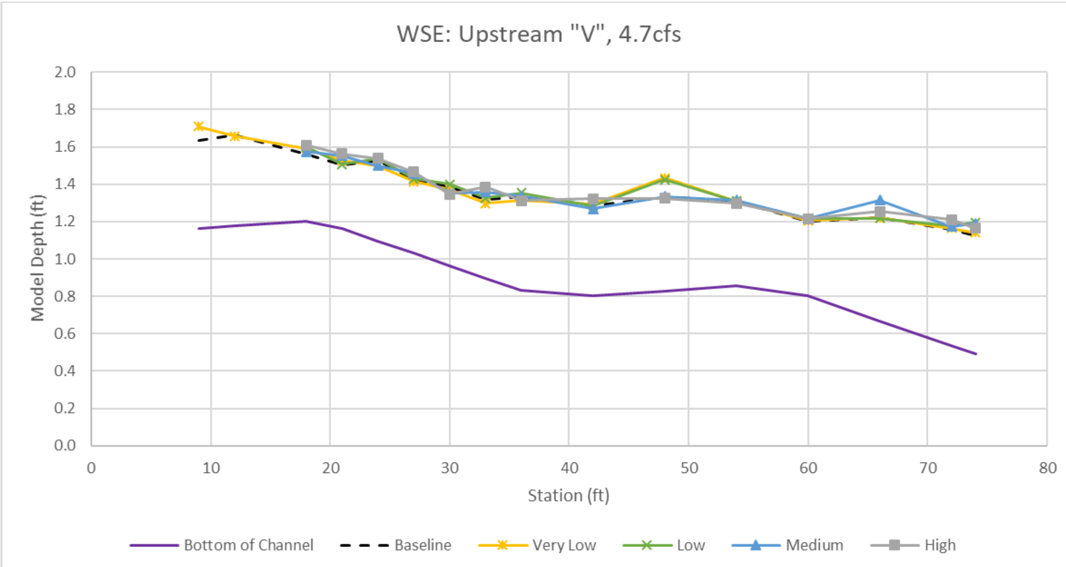

Figure 8 Water surface and channel invert profiles for small rock configurations at 4.7 cfs. Clusters were located between station 18 and 36.

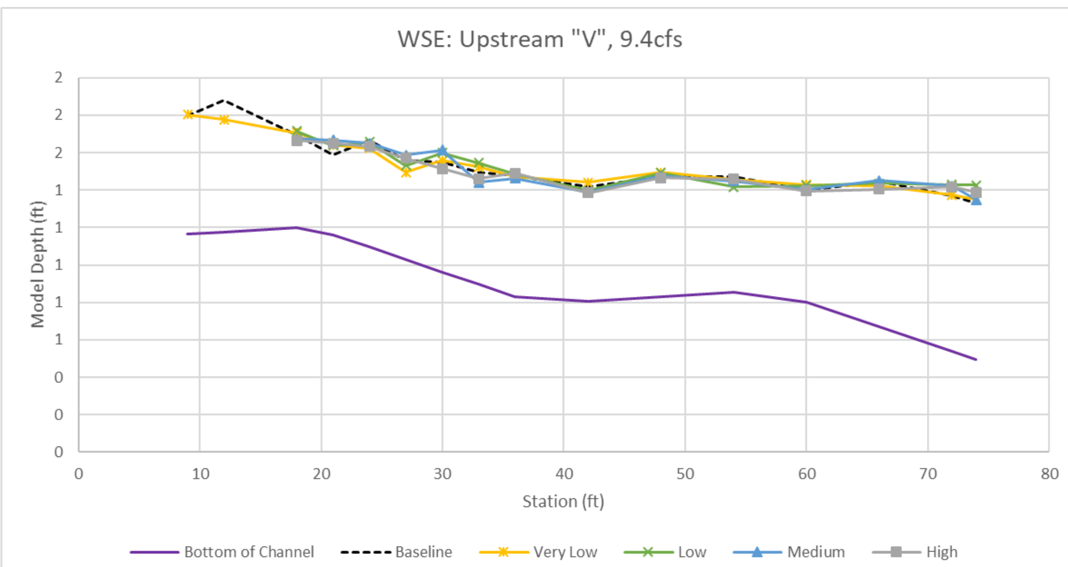

Figure 9 Water surface and channel invert profiles for small rock configurations at 9.4 cfs. Clusters were located between station 18 and 36.

Dimensionless Analysis

The dimensionless analysis aimed to increase the applicability of physical model test results by considering changes in the velocity caused by boulder clusters relative to the flow rate, density, and type of configuration. Non-dimensionalizing the analysis allows a designer to more readily scale the laboratory results to different field sites. After the baseline hydraulics are determined, the hydraulics for boulder cluster installations could be estimated using the dimensionless terms. The parameters of interest for dimensionless analysis were: 1) percent plan view area blocked; 2) percent cross-section area blocked; 3) percent volume blocked.

Percent plan view area blocked was plotted against the average velocity, average velocity ratio (VR_{AVG}), standard deviation, and standard deviation ratio (SDR_V) (Figure 10 through Figure 13). Single rock configurations had a higher average velocity and velocity ratio than baseline at the highest and lowest flow rates. However, the average velocity was decreased when more rocks were added. Furthermore, single rocks had the lowest variability in standard deviation relative to the standard deviation of the baseline tests (SDR_V), indicating that this configuration does not create as much variability in the velocity field as other configuration types when compared to baseline conditions at the same flow rate. Upstream and Downstream V configurations were the most efficient at reducing velocity given the plan view area blocked. The standard deviation ratio for the Upstream V configuration had more variability than the Downstream V for the highest and lowest flow rates. Thus, the Downstream V has a more consistent velocity distribution over a range of flows. Finally, the Diamond was effective at lowering the velocity, however as it had significantly more plan view area blocked and not consistently lower velocity, it may not be cost effective for many projects. There is a consistent trend of decreasing average velocity as the percent plan view area blocked increases; however, this trend is less apparent for tests with an area blocked at or above about 3 percent. This indicates there may be an optimal value around 2 to 3 percent blocked.

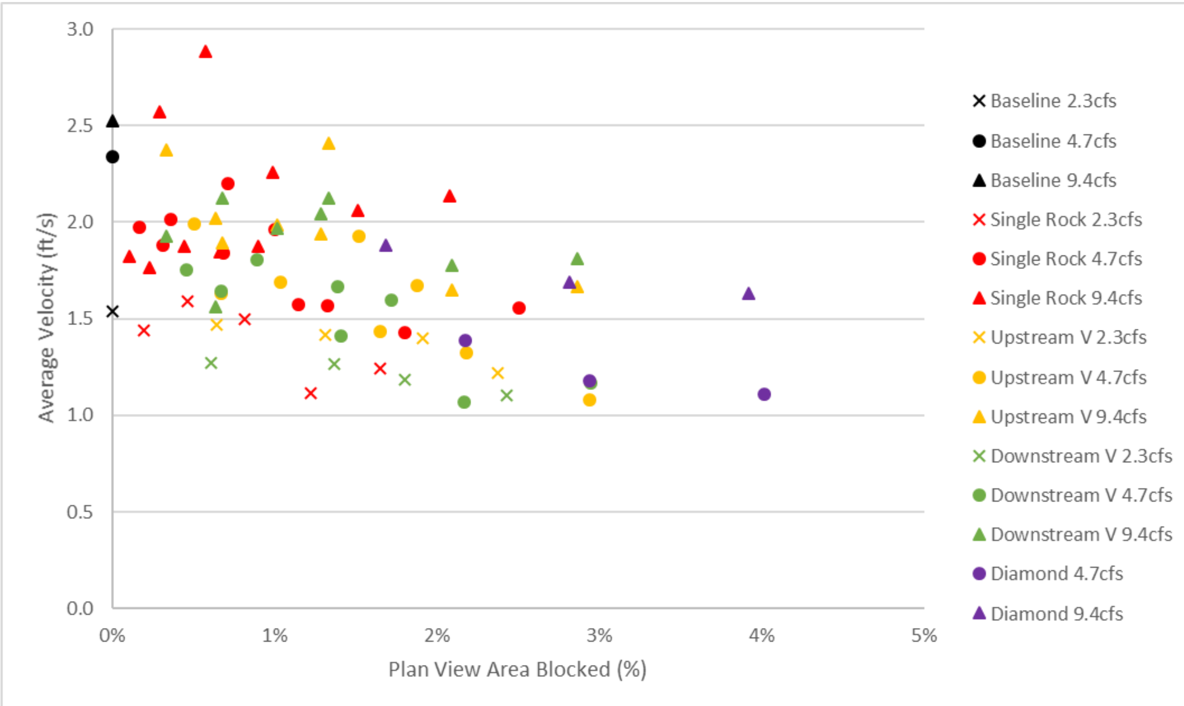

Figure 10 Percent plan view area blocked for every configuration and average velocity. Each configuration represents both small and large rock tests.

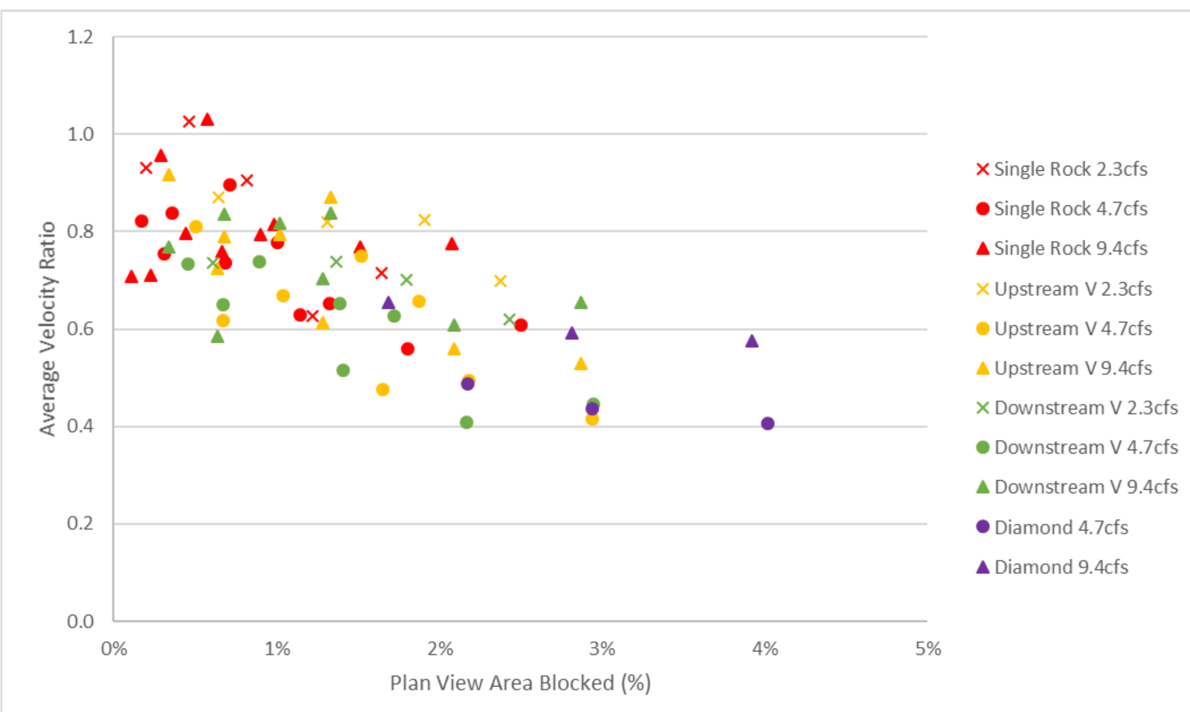

Figure 11 Percent plan view area blocked for every configuration and average velocity ratio. The average velocity ratio is the average velocity per test taken with respect to the corresponding baseline average velocity for each flow rate. Each configuration represents both small and large rock tests.

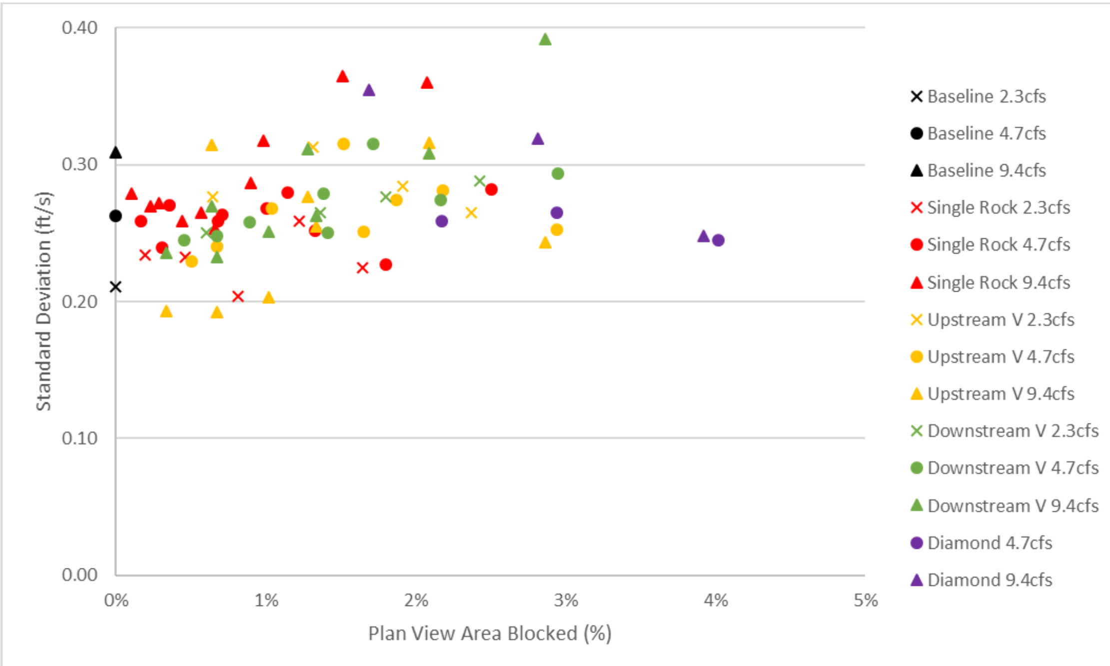

Figure 12 Percent plan view area blocked for every configuration and standard deviation. Each configuration represents both small and large rock tests.

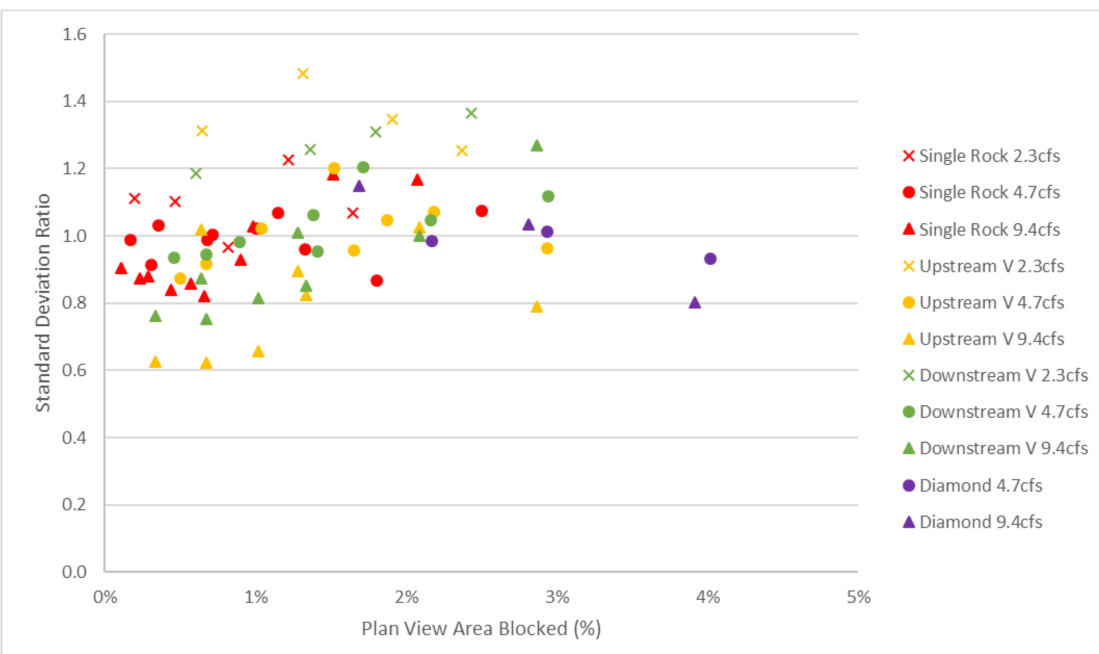

Figure 13 Percent plan view area blocked for every configuration and the standard deviation ratio. The standard deviation ratio is the standard deviation per test taken with respect to the corresponding baseline standard deviation for each flow rate. Each configuration represents both small and large rock tests.

A similar trend can be seen in the percent cross-sectional area blocked (Figure 14 through Figure 17). The percent cross-sectional area blocked is representative of the space obstructed by the single rock or the boulder cluster in the width of the channel. The single rock resulted in higher average velocities for some tests but was generally efficient at lowering the velocities considering the relatively low cross-sectional areas blocked. The trend of decreasing average velocity associated with increasing percent cross-sectional area blocked is less clear for the single rocks, possibly because the percent blocked never exceeds 20 percent. An anomaly that should be noted is that the Diamond configuration obstructed less of the cross-sectional area for the highest flow rate than the Upstream and Downstream V counterparts. This is due to the boulder properties of the additional rock in the configuration. Often, the rock in the most downstream position of the diamond was smaller than those further upstream. These smaller dimensions would decrease the average cross-sectional area of a cluster because the cluster height was calculated by averaging the height of all rocks in a cluster. The Upstream and Downstream V performed similarly with the Downstream V proving slightly less efficient at the lowest cross-sectional area blocked (or density of clusters). The Downstream V effectiveness steadily increased as more rocks were added, compared with the Upstream V that obstructs more flow but had little change in the velocity reduction. It appears that a percent cross-sectional area blocked of about 30-40% is optimal, since higher percent blockages do not appear to reduce the average channel velocity.

The previous variable, plan view area blocked, was not dependent on depth, especially when increasing from the bankfull flow of 4.7 cfs to the highest flow of 9.4 cfs. Therefore, as discharge increased above bankfull, the velocity was increased for the same plan view area blocked. Analyzing cross-sectional area blocked provides additional insight. The greatest cross-sectional area blocked, and the greatest velocity reduction, occurs at the bankfull flow of 4.7 cfs. The flow depth at this discharge is near the top of the boulder crests. Increasing flow depth above the boulders causes a reduction in cross-sectional area blocked and an increase in average velocity.

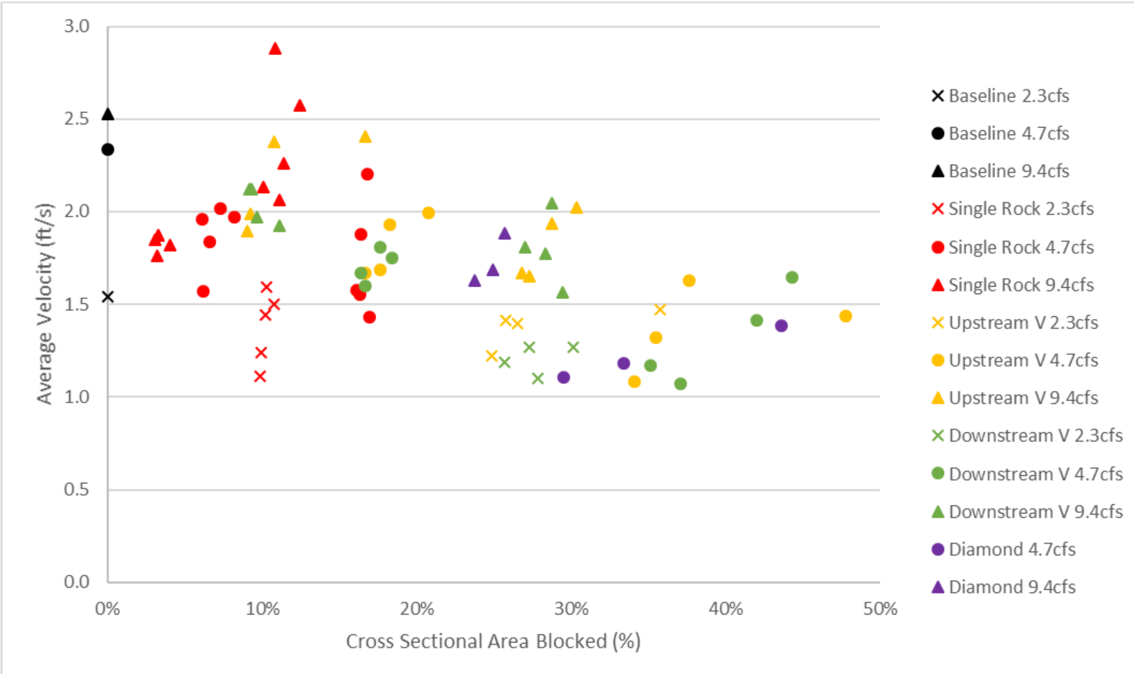

Figure 14 Percent cross-sectional area blocked for every configuration and average velocity. Each configuration represents both small and large rock tests.

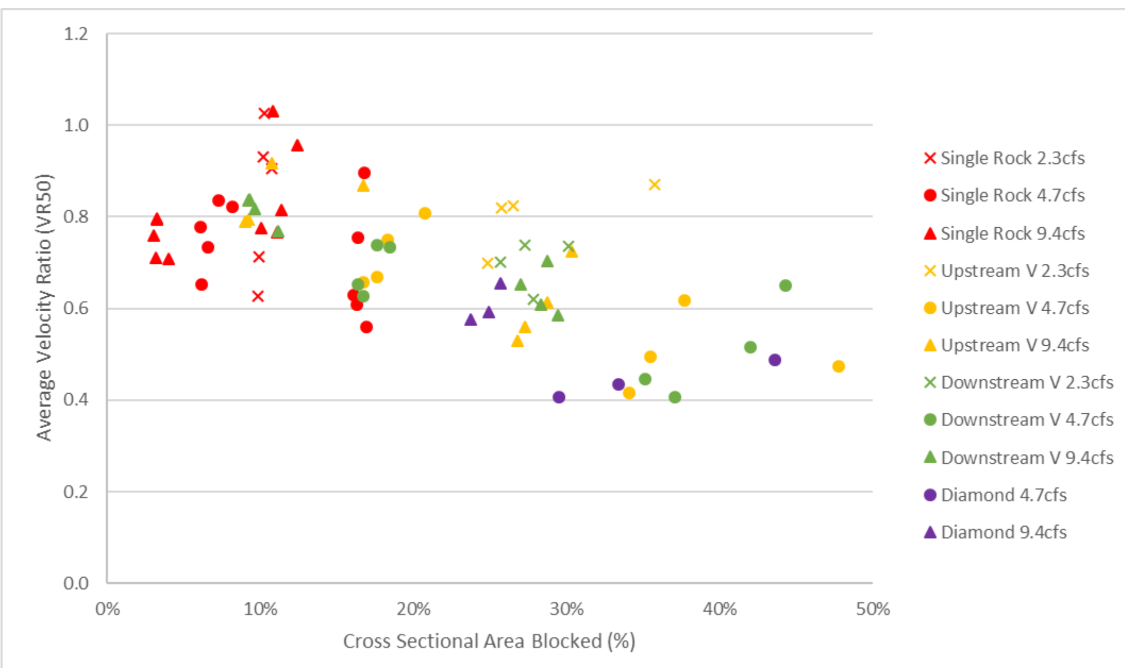

Figure 15 Percent cross-sectional area blocked for every configuration and average velocity ratio. The average velocity ratio is the average velocity per test taken with respect to the corresponding baseline average velocity for each flow rate. Each configuration represents both small and large rock tests.

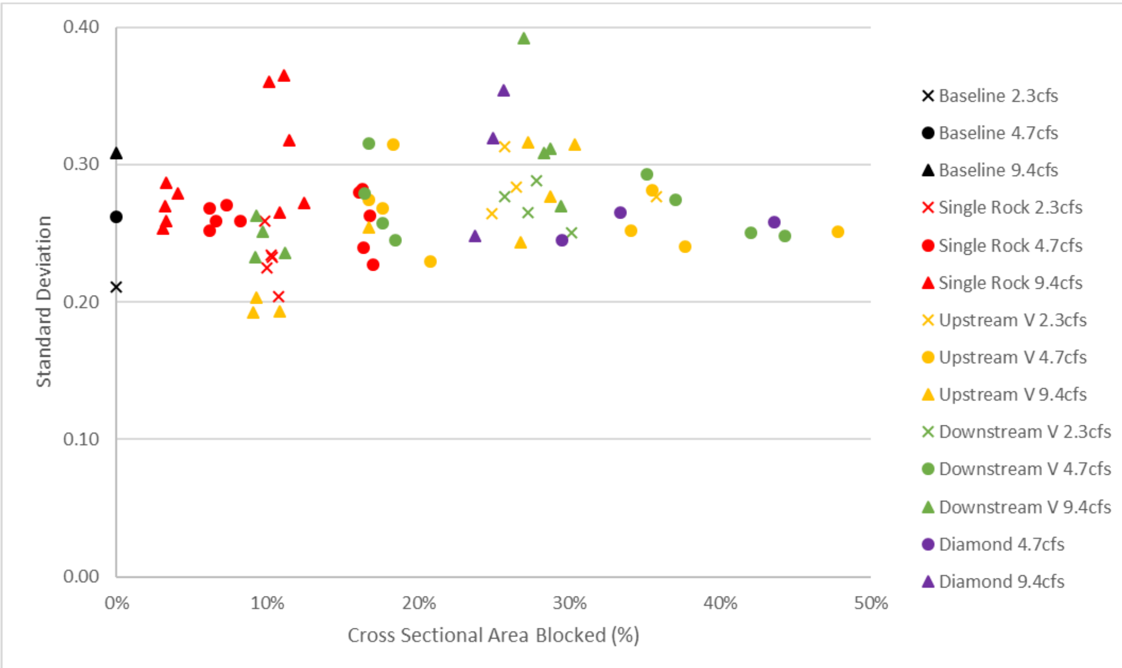

Figure 16 Percent cross-sectional area blocked for every configuration and standard deviation. Each configuration represents both small and large rock tests.

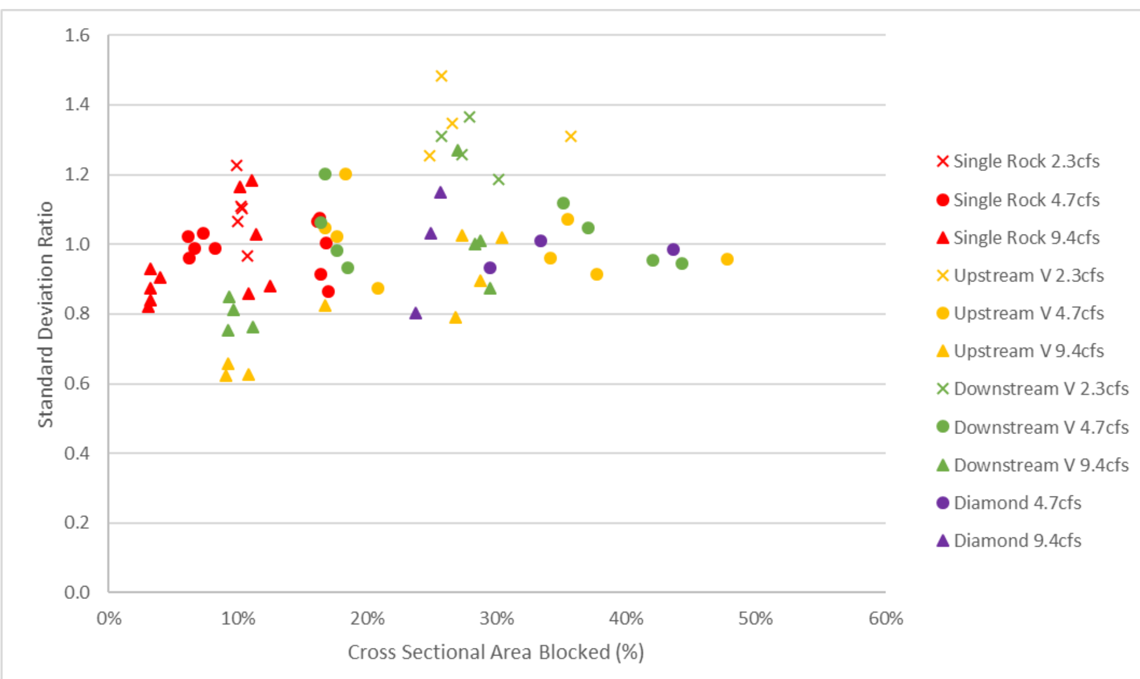

Figure 17 Percent cross-sectional area blocked for every configuration and the standard deviation ratio. The standard deviation ratio is the standard deviation per test taken with respect to the corresponding baseline standard deviation for each flow rate. Each configuration represents both small and large rock tests.

As the percent volume blocked increases, the average velocity and velocity ratio decreases regardless of configuration used. This makes the percent volume an important variable when considering the configuration to use based on site-specific constraints. For every additional percent obstructed, the average velocity ratio is reduced by 0.1 to 0.2. Though the Diamond configuration has the highest percent volume blocked, it does not significantly improve the velocity ratio when compared to the Upstream and Downstream V. When comparing similar volume blocked, the Upstream and Downstream V have the greatest reduction of velocity. However, the single rock configuration fares well in comparison at the smallest volume blocked, between 0 to 1%, thus demonstrating the usefulness of small rocks in conditions with limited space or when limited rocks are available to use for restoration. The standard deviation remains consistent for all configurations even as percent volume blocked increases for the lower flow rates. There is a spike for the highest (9.4 cfs) flow rate for nearly all configurations as the volume blocked increases. The standard deviation tends to increase as both the flow rate and velocity increase. However, the standard deviation ratio remains close to 1 for most tests (typically between 0.8 and 1.2). This indicates that boulder clusters reduce the average velocity and change the spatial distribution of velocity, but they do not appreciably change the variance and range in velocity values. Essentially, boulder clusters relocate the lowest velocity areas from the channel margins to areas of deeper water near the boulders. Since data was only collected up to about a 4% volume blockage by boulders, it is not possible to determine the optimal percent blockage by volume. Testing with higher percent volume blockages would be required. Using percent volume blocked as the dependent variable results in the strongest correlation and the best prediction of variance in the average velocity ratio. The variables of percent plan view area blocked and percent cross-sectional area blocked also performed well, but there was more scatter in the average velocity trends.

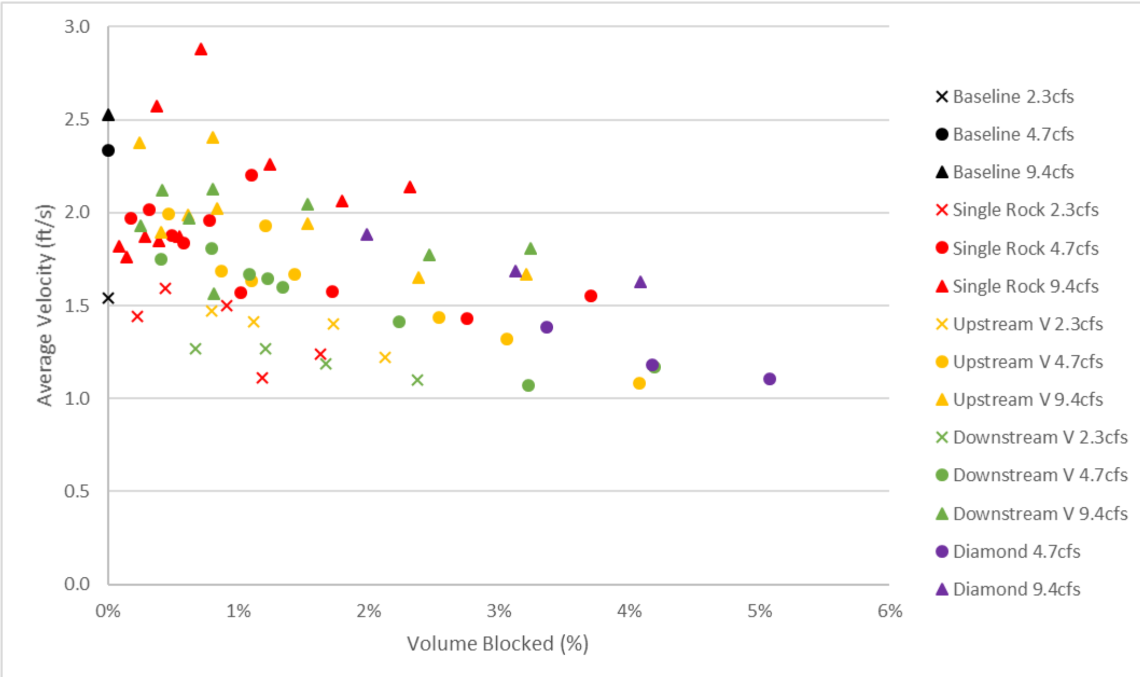

Figure 18 Percent volume blocked for every configuration and average velocity. Each configuration represents both small and large rock tests.

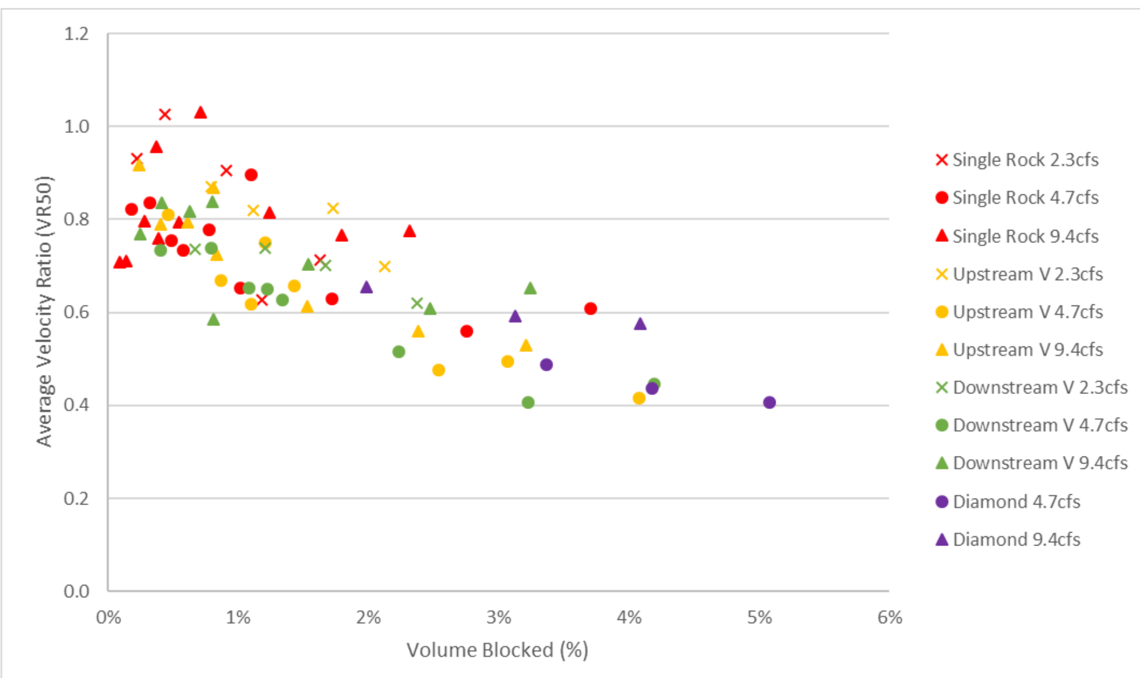

Figure 19 Percent volume blocked for every configuration and average velocity ratio. The average velocity ratio is the average velocity per test taken with respect to the corresponding baseline average velocity for each flow rate. Each configuration represents both small and large rock tests.

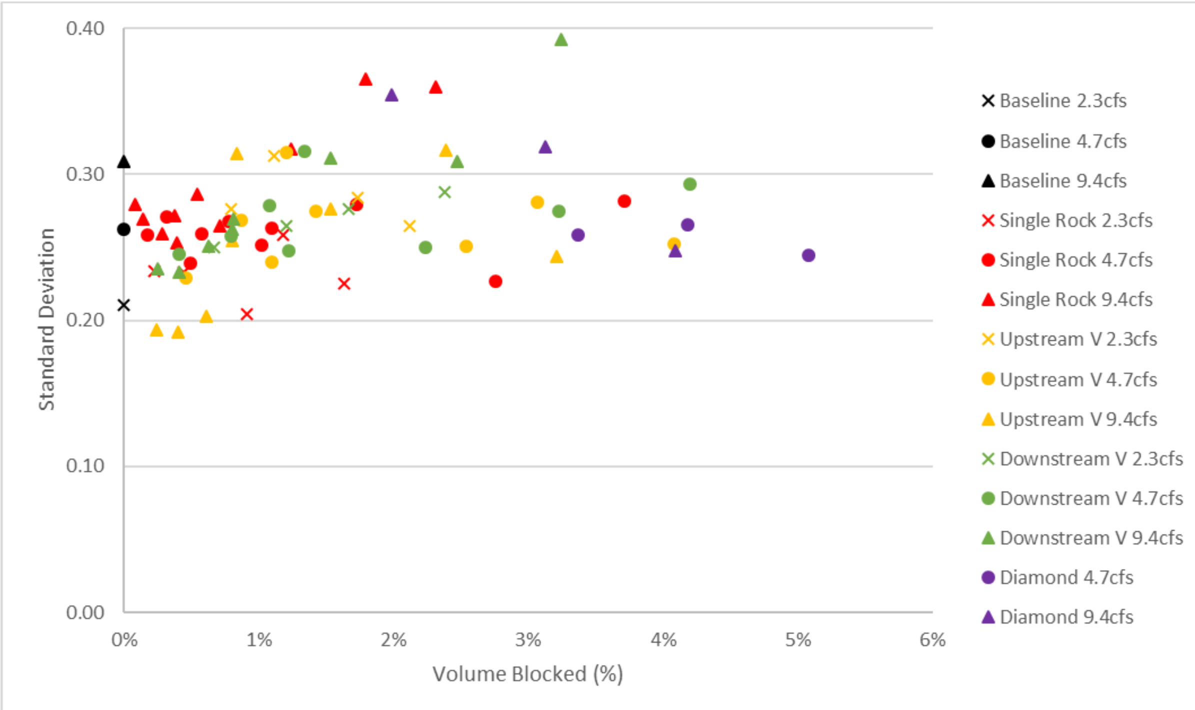

Figure 20 Percent cross-sectional area blocked for every configuration and standard deviation. Each configuration represents both small and large rock tests.

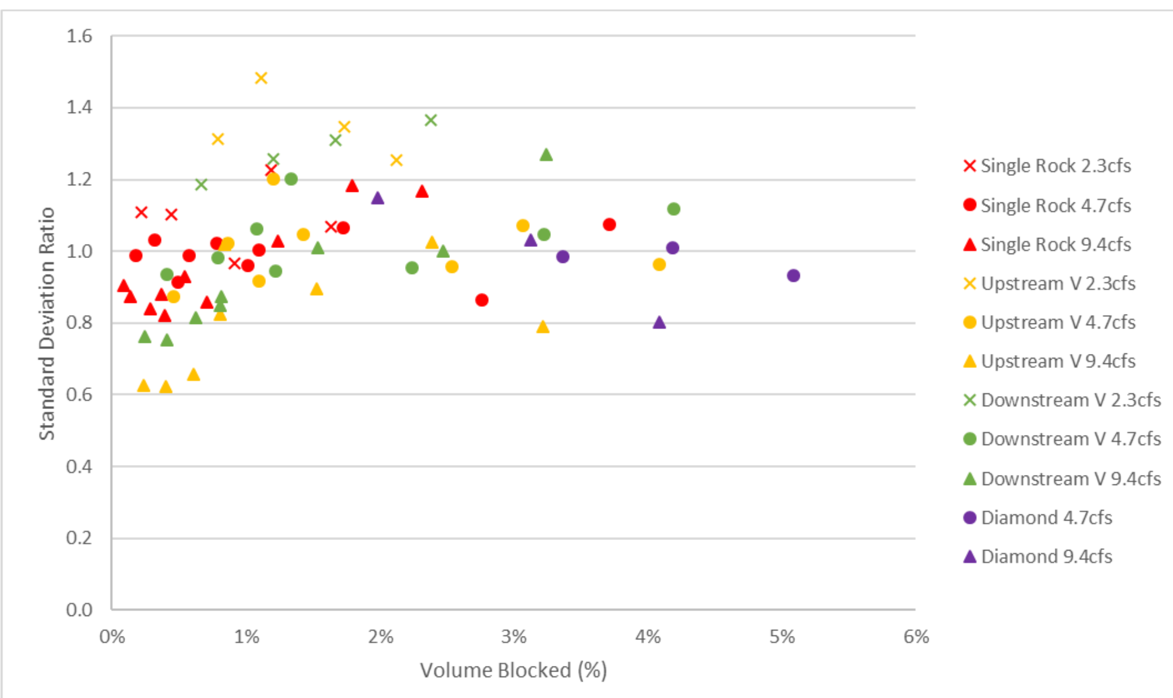

Figure 21 Percent cross-sectional area blocked for every configuration and the standard deviation ratio. The standard deviation ratio is the standard deviation per test taken with respect to the corresponding baseline standard deviation for each flow rate. Each configuration represents both small and large rock tests.

Velocity Analysis

CDF and PDF curves were generated for each configuration using all available velocity points from LSPIV data collection (Appendix C and D).

Velocity analysis focused on generating ratios of velocities for each configuration to the corresponding baseline velocity from the CDF curves (Appendix C: Velocity Distribution Curves). A number less than 1 for these ratios indicates the velocity at this given percentile (e.g., the median) has been reduced by the boulder configuration, a number greater than 1 indicates the velocity at this percentile has been increased by the boulder configuration. All configurations, regardless of density or flow rate, exhibited the trend of converging to the ratio of 1 as the percentile increased (Figure 24 and Figure 25, Appendix E). The maximum velocity (represented as 100 on the x-axis) for both the baseline and the boulder configurations were similar.

Deviations from the baseline at the lower velocity percentiles can be explained by the masking process during analysis and the CDF curves. Masking was applied during the early phase of processing to preclude areas of no flow or extremely shallow flow from the PIVLab software (Data Collection Methods: Large-Scale Particle Image Velocimetry (LSPIV or PIV)). However, as each configuration and flow rate had different areas of shallow flow, the mask was not uniformly applied to each test. To account for the impacts of the mask, CDF curves were generated (Appendix C: Velocity Distribution Curves (CDF)). When masks are applied in PIVLab, the resulting velocity vectors appear as 0 ft/s. Thus, the CDF curves show what percentage of the channel are masked with a zero velocity. For instance, in the small rock Upstream V test at 4.7 cfs, the baseline and the majority of the configurations have approximately 25% masked (Figure 22). The medium density configuration, however, has less than 10% masked resulting in deviations from the baseline curve. The impacts of this masking procedure are most pronounced at the minimum, 10%, and 25% velocity percentiles. In the CDF curves, this results in the configurations with rocks appearing under the baseline curve. This means the velocities are higher than they would be at baseline. However, around the 50th percentile (median), the cluster curves cross over the baseline, lowering the velocities at these upper percentiles. For the large rock Upstream V at 4.7 cfs, all curves for the cluster configurations are higher. This results in lower velocities at all percentiles when compared to the baseline, though velocities at each percentile differ because of the masking (Figure 23).

For the velocity ratio analysis, the masks with zero velocity values were excluded. This caused a shift in the lower range of percentiles that often deviated greatly from the baseline (Figure 24 and Figure 25, Appendix E). An example of this is the large single rock configurations for the 9.4 cfs flow rate for velocity ratios less than the median (50) percentile. These large rocks were designed to be overtopped at 9.4 cfs, however the tallest rocks were still near the water surface, causing areas of rapid flow acceleration. As most clusters tended to be at the boundary with the masks due to their placement in the channel, the flow acceleration increased between the boulder edges and the channel margins, causing the minimum, 10% and 25% velocity percentiles to be higher. This yielded a ratio greater than 1.

A similar example for the small rocks occurs at the middle flow rate as these rocks were designed to be overtopped at 4.7 cfs as opposed to 9.4 cfs for the large rocks. During the single rock configuration, the minimum velocity ratio was very similar to the baseline. However, the velocity ratios diverged rapidly from the baseline at the first (25) quartile before converging again at the maximum flow. This is due to the removal of the masks and the increase of velocity at the boundary conditions with the masked portion. For the high (9.4 cfs) flow rate the smaller rocks were submerged and thus did not create those areas of high velocity at the boundary. Even though the rocks were submerged, they still created disruptions at the surface, decreasing the velocity. This lowers the ratio to be less than 1 at these smaller percentiles.

The large rock Upstream V, Downstream V and Diamond configurations were the most efficient at keeping the velocity ratios under 1. Very few configurations presented an increase in velocity caused by the boulder configurations for both large and small rocks. Overall, the clusters reduced the velocity in the channel, however the minimum velocities were greater than baseline. As many boulder clusters abutted the margin of the mask along almost the entire region of analysis, this may have increased the minimum, 10%, and 25% velocity percentiles due to flow acceleration between the boulder edges and the channel margins.

The small rock Upstream V configuration often caused an increase to the velocity at the minimum ratio as a function of the density of clusters. The "very low" (one cluster) density increased the minimum velocity even at the lowest flow rate due to the presences of the masking. The solitary cluster was not enough to lower the velocity in the channel beyond a region immediately adjacent to the cluster but still increased the velocity at the boundary with the mask, resulting in the minimum velocity in the channel appearing higher than at baseline conditions. Conversely, the small rock Downstream V was efficient at keeping all velocity ratios under 1 due to the backwater effect caused by the Downstream V immediately upstream of the clusters. The backwater effect would decrease velocities around the clusters, near the boundary of the mask, thus reducing the velocity and the velocity ratio. However, this same backwatering may cause issues for the large rock clusters if channel capacity is limited. Thus, the Downstream V for small rocks and the Upstream V for large rocks could be a potential combination for effectively reducing the flows without causing significant backwatering.

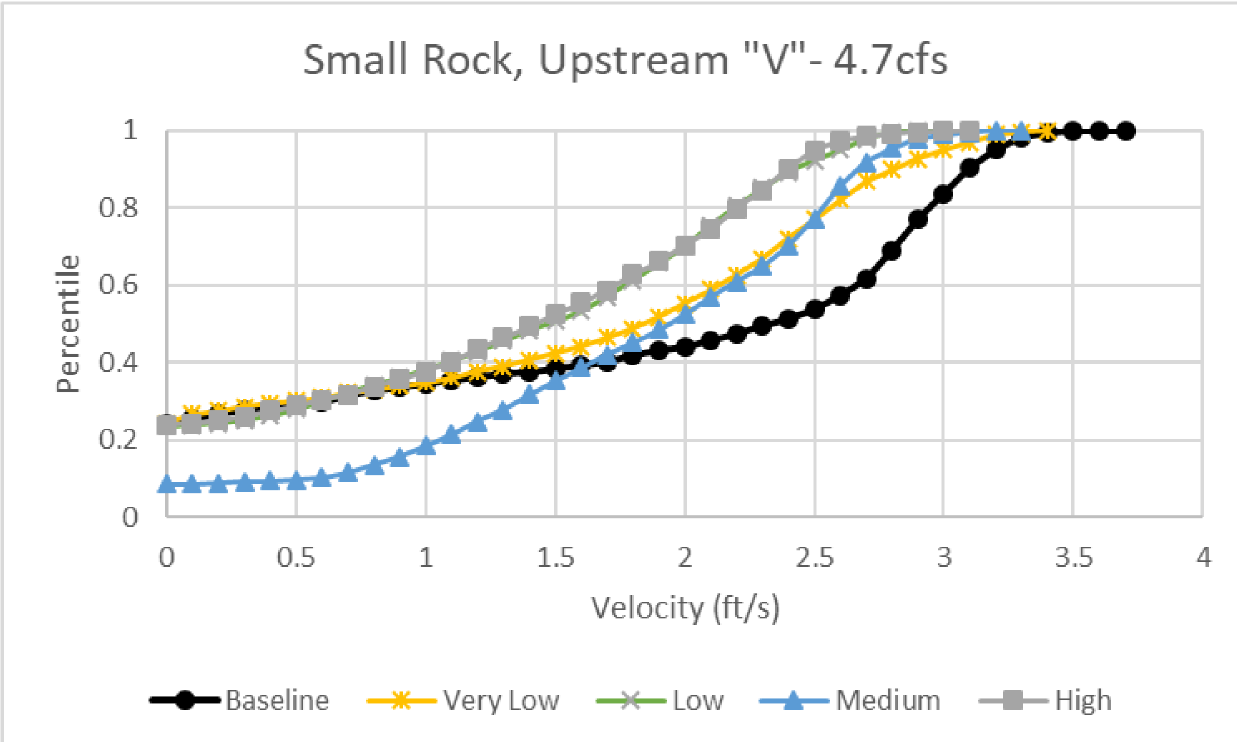

Figure 22 Cumulative distribution function for small rock, Upstream V at 4.7 cfs.

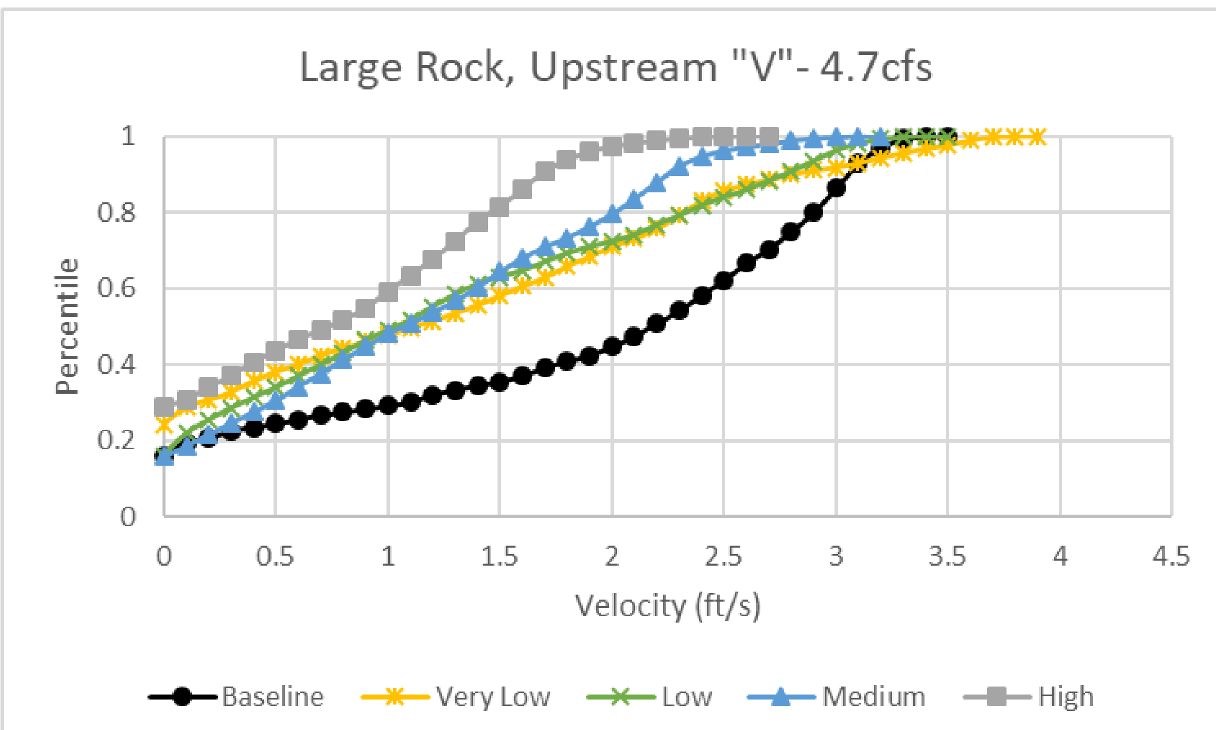

Figure 23 Cumulative distribution function for large rock, Upstream V at 4.7 cfs.

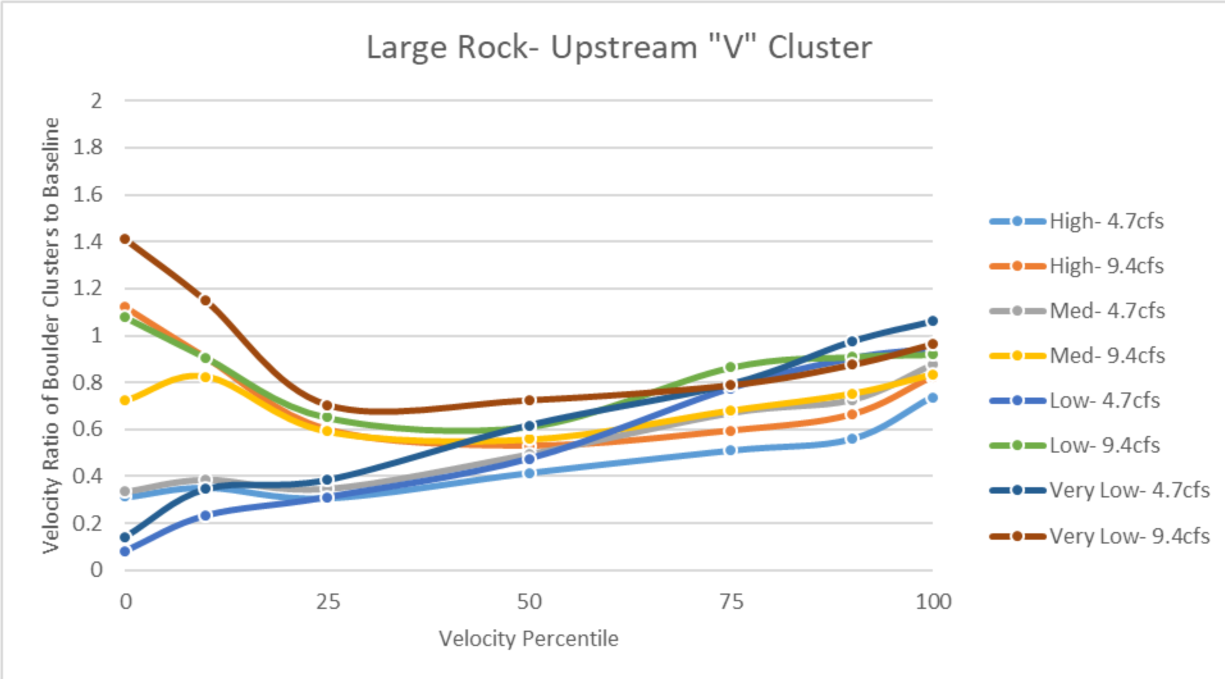

Figure 24 The ratio of cluster velocity to baseline over the velocity percentiles for large rock, Upstream V configuration at all densities and tested flow rates.

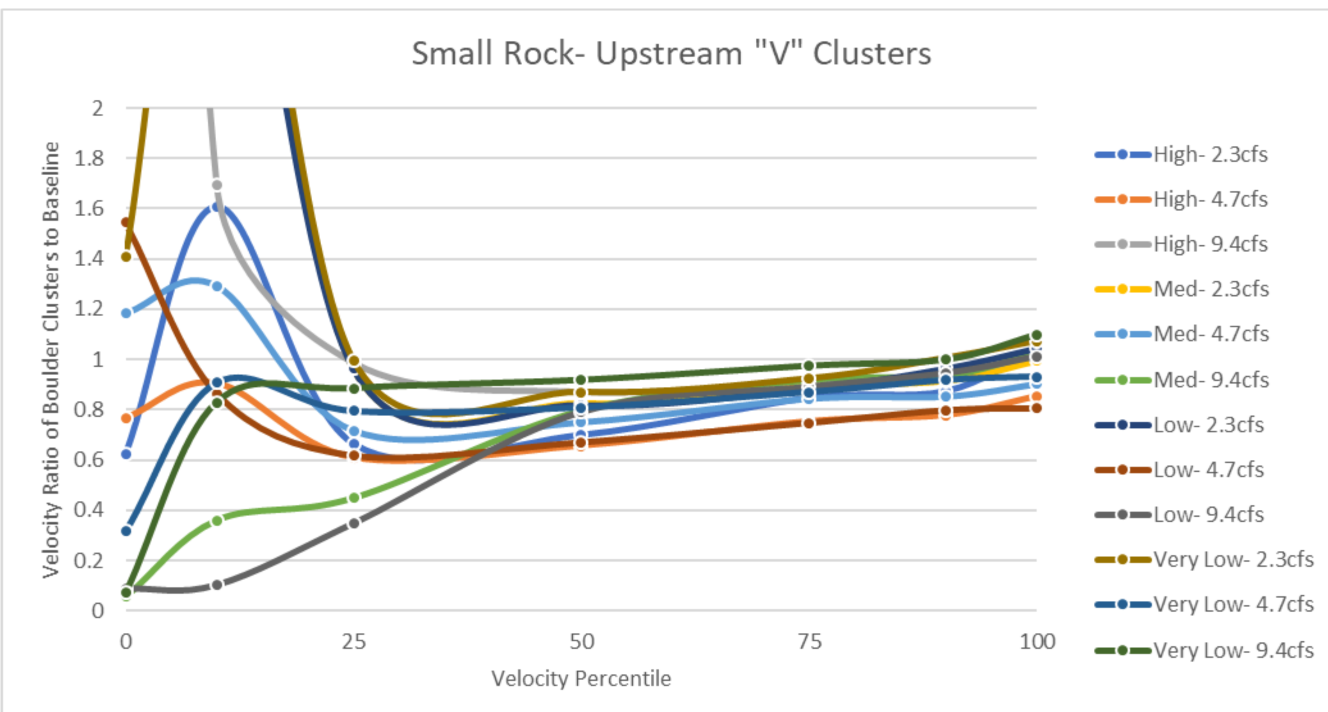

Figure 25 The ratio of cluster velocity to baseline over the velocity percentiles for small rock, Upstream V configuration at all densities and tested flow rates.

Conclusions and Recommendations

Conclusions

Dimensionless analysis aimed to increase the applicability of physical model test results by considering changes in the velocity caused by boulder clusters relative to the flow rate, density, and type of configuration. The boulders were tested at two different sizes (large and small) for three different flow rates (2.3, 4.7, and 9.4 cfs) over four different configurations (single rock, upstream v, downstream v, and diamond). These were deployed at 5 different densities for single rocks (high, medium high, medium, low, and very low) and 4 densities for cluster configurations (high, medium, low, and very low).

The parameters of interest for dimensionless analysis were: 1) percent plan view area blocked; 2) percent cross-section area blocked at the single rock or boulder cluster; 3) percent volume blocked. These parameters were compared to the average velocity, velocity ratio, standard deviation, and standard deviation ratio. The velocity ratios of each configuration were derived from cumulative distribution functions (CDF) for minimum, quartiles, and maximum values. These values were then related to the corresponding baseline flow rate to determine the ratios. The standard deviation of these ratios was then calculated. A ratio value of less than 1 means the boulder configuration was more efficient at slowing flow than at baseline where no rocks are present.

For the percent plan view area blocked, Upstream and Downstream V configurations perform best relative to boulder density, though this trend of reduced velocity was not significantly improved with the percentage of plan view area blocked due to the small percentages tested. All configurations blocked between 0.5 to 4% of the plan view area, making the margin for improvement per configuration very slight. The Upstream and Downstream V configurations occupied between 0.5 to 3% of the plan view area and resulted in velocity ratios of 0.4 to 0.85 for the Upstream V and 0.4 to 0.95 for the Downstream V. Single rocks often had ratios of greater than 1 at higher and lower flow rates but performed well at the middle flow rate with the smallest percent plan view occupied (between 0.2 to 2.2%). Thus, small rocks may be suitable in smaller channels where fluctuations in flow rates are not common. The diamond configuration reduced the velocity the most with a ratio between 0.4 to 0.65, however clusters occupied more space and would be less cost efficient due to the addition of extra rocks.

For the percent cross-sectional area blocked at the single rock or boulder cluster, there was a decreasing trend of velocity ratio for cross-sectional area blocked, meaning the more cross-sectional area obstructed by rocks, the more effectively the velocity is reduced in the channel. However, the trend does not significantly improve after 35%. Therefore, the ideal amount of cross-sectional channel area obstructed is between 30 to 40%. The Downstream V was more efficient than Upstream V when more clusters were utilized and had less fluctuations in the standard deviation associated with it. Therefore, Downstream V configurations may be utilized in a river system subject to varying flow rates should there be space for more clusters.

At 0 to 1% volume blocked, velocity ratios were consistently between 0.6 and 1. Once 2 to 4% of the volume was blocked, all ratios fell below 0.65 for all configurations. Even the single rock configuration performed well (0.58) when obstructing 2.8% of the channel.

During the velocity analysis, there were discrepancies in the velocity ratio at the minimum and lower percentiles caused by masking. Masking was applied during the early phase of processing to preclude area of no flow or extremely shallow impassable flow from the PIVLab software. However, as the portion of the channel without flow differed for each configuration, a different mask was applied for each test. The resulting output yielded a zero value for the masked portion of the dataset. Thus, the CDF curves aimed to eliminate the impacts from the masks. When the masked portions were removed from the dataset to create the ratio of velocity intervals to baseline, the resulting data for the baseline had very low velocities along the channel margins. As many boulder clusters abutted the margin of the mask, this may have increased the minimum, 10%, and 25% velocity percentiles due to flow acceleration between the boulder edges and the channel margins. This is especially apparent in the single rock configuration presented at the highest and lowest flow rates.

However, this was not an issue for all configurations. The large rock Upstream V only had three points above a velocity ratio of 1, meaning it was effective at reducing flows throughout the channel. Similarly, all values except one for the small rock Downstream V had a velocity ratio less than 1. This means that an effective combination may be to use small and large rocks in the Downstream and Upstream V configuration. For example, the small rocks could be used in a Downstream V configuration where water surface elevation requirements may be more stringent, while large rocks in an Upstream V configuration could be used where slowing the flow is paramount to the success of creating resting habitat. Furthermore, all configurations converged to 1 or slightly less than 1 for the maximum velocity ratio, reducing the velocity overall and thus improving conditions in the channel.

Recommendations

The data presented in this report should be further analyzed and used to develop boulder cluster design guidelines. The spatial distribution of velocity, in combination with depth, should be further considered. A more rigorous and quantitative method should be developed for predicting the size and location of low velocity areas associated with different boulder cluster configurations. Furthermore, a composite Manning's roughness value could be computed for the channel for the different boulder configurations to increase model accuracy. This would help give designers better tools for optimizing boulder placement depending on specific habitat goals. 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.

The data from the boulder physical model tests should be compared with a 2D numerical model for various laboratory configurations to see how 2D models can best simulate complex hydraulics associated with boulder clusters. Numerical models could then be used to assess project specific designs.

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Appendix A: Boulder and Flow Properties

Table A- 1 Individual boulder properties. LR denotes "Large Rock"; SR denotes "Small Rock". Please see Analysis Methods for a comprehensive definition of variables.

Boulder Number	X_B (ft)	Y_B (ft)	Z_B (ft)	A_{P-B} (ft^2)	A_{XS-B} (ft^2)	VOL_B (ft^3)
LR-1	0.65	1.02	0.65	0.66	0.66	0.43
LR-2	0.78	1.06	0.60	0.83	0.64	0.50
LR-3	0.77	0.97	0.75	0.75	0.73	0.56
LR-4	0.63	0.94	0.56	0.59	0.53	0.33
LR-5	0.73	1.04	0.65	0.76	0.67	0.49
LR-6	0.71	1.06	0.66	0.75	0.70	0.49
LR-7	0.96	0.83	0.61	0.80	0.51	0.49
LR-8	0.79	1.02	0.63	0.81	0.64	0.51
LR-9	0.89	0.85	0.63	0.76	0.53	0.47
LR-10	0.85	1.09	0.53	0.93	0.58	0.50
LR-11	0.69	0.83	0.63	0.57	0.52	0.36
LR-12	0.46	0.92	0.58	0.42	0.53	0.25
LR-13	0.63	0.98	0.58	0.61	0.57	0.36
LR-14	0.70	1.31	0.65	0.92	0.85	0.59
LR-15	0.50	1.02	0.56	0.51	0.57	0.29
LR-16	0.54	1.00	0.60	0.54	0.60	0.33
SR-1	0.54	0.58	0.33	0.32	0.19	0.11
SR-2	0.57	0.54	0.40	0.31	0.21	0.12
SR-3	0.60	0.48	0.40	0.29	0.19	0.12
SR-4	0.58	0.60	0.28	0.35	0.17	0.10
SR-5	0.56	0.63	0.29	0.35	0.18	0.10
SR-6	0.48	0.58	0.25	0.28	0.15	0.07
SR-7	0.50	0.67	0.29	0.33	0.19	0.10
SR-8	0.56	0.60	0.27	0.34	0.16	0.09
SR-9	0.50	0.50	0.33	0.25	0.17	0.08
SR-10	0.58	0.54	0.33	0.32	0.18	0.11
SR-11	0.58	0.58	0.29	0.34	0.17	0.10
SR-12	0.58	0.58	0.33	0.34	0.19	0.11

Table A- 2 Individual Cluster Properties. LR denotes "Large Rock"; SR denotes "Small Rock". S denotes "Single Rock"; V denotes a cluster (upstream and downstream V). Please see Analysis Methods for a comprehensive definition of variables.

Cluster Number	Boulders Used	Y_{BC} (ft)	$\overline{Z_B}$ (ft)	$A_{P\text{-}BC}$ (ft^2)	$A_{XS\text{-}BC}$ (ft^2)	VOL_{BC} (ft^3)
LR-S-1	1	1.02	0.65	0.66	0.66	0.43
LR-S-2	2	1.06	0.60	0.83	0.64	0.50
LR-S-3	3	0.97	0.75	0.75	0.73	0.56
LR-S-4	4	0.94	0.56	0.59	0.53	0.33
LR-S-5	5	1.04	0.65	0.76	0.67	0.49
LR-S-6	6	1.06	0.66	0.75	0.70	0.49
LR-S-7	7	0.83	0.61	0.80	0.51	0.49
LR-S-8	8	1.02	0.63	0.81	0.64	0.51
LR-V-1	1, 8, 9	2.58	0.63	2.22	1.83	1.40
LR-V-2	2, 11, 12	2.54	0.60	1.82	1.70	1.10
LR-V-3	3, 7, 5	2.63	0.67	2.30	1.91	1.54
LR-V-4	4, 6, 15	2.79	0.59	1.85	1.80	1.11
LR-D-1	1, 8, 9, 10	2.58	0.61	3.16	2.41	1.90
LR-D-2	2, 11, 12, 13	2.54	0.60	2.44	2.27	1.46
LR-D-3	3, 7, 5, 14	2.63	0.66	3.22	2.76	2.13
LR-D-4	4, 6, 15, 16	2.79	0.48	2.39	2.40	1.44
SR-S-1	1	0.58	0.33	0.32	0.19	0.11
SR-S-2	2	0.54	0.40	0.31	0.21	0.12
SR-S-3	3	0.48	0.40	0.29	0.19	0.12
SR-S-4	4	0.60	0.28	0.35	0.17	0.10
SR-S-5	5	0.63	0.29	0.35	0.18	0.10
SR-S-6	6	0.58	0.25	0.28	0.15	0.07
SR-S-7	7	0.67	0.29	0.33	0.19	0.10
SR-S-8	8	0.60	0.27	0.34	0.16	0.09
SR-V-1	1, 9, 8	1.67	0.31	0.91	0.52	0.28
SR-V-2	2, 11, 10	1.63	0.34	0.96	0.57	0.33
SR-V-3	3, 5, 7	1.75	0.33	0.97	0.57	0.32
SR-V-4	4, 6, 12	1.63	0.29	0.97	0.51	0.28

Table A- 3 Test configurations and boulder properties for large rocks. Please see Analysis Methods for a comprehensive definition of variables.

Test #	Config	Density	# Clusters	# Boulders	Flow (cfs)	Plan View Area Blocked (%)	Average Cross-section Area Blocked (%)	Volume Blocked (%)
a	Baseline	N/A	0	0	2.3	0%	0%	0%
b	Baseline	N/A	0	0	4.7	0%	0%	0%
c	Baseline	N/A	0	0	9.4	0%	0%	0%
L-1	Single	Medium	4	4	4.7	1%	16%	2%
L-2	Single	Medium	4	4	9.4	1%	11%	1%
L-3	Single	Med-High	6	6	4.7	2%	17%	3%
L-4	Single	Med-High	6	6	9.4	2%	11%	2%
L-5	Single	High	8	8	4.7	3%	16%	4%
L-6	Single	High	8	8	9.4	2%	10%	2%
L-7	Single	Low	2	2	4.7	1%	17%	1%
L-8	Single	Low	2	2	9.4	1%	11%	1%
L-9	Single	Very Low	1	1	4.7	0%	16%	0%
L-10	Single	Very Low	1	1	9.4	0%	12%	0%
L-11	Upstream "V" Cluster	High	4	12	4.7	3%	34%	4%
L-12	Upstream "V" Cluster	High	4	12	9.4	3%	27%	3%
L-13	Upstream "V" Cluster	Medium	3	9	4.7	2%	35%	3%
L-14	Upstream "V" Cluster	Medium	3	9	9.4	2%	27%	2%
L-15	Upstream "V" Cluster	Low	2	6	4.7	2%	48%	3%
L-16	Upstream "V" Cluster	Low	2	6	9.4	1%	29%	2%
L-17	Upstream "V" Cluster	Very Low	1	3	4.7	1%	38%	1%
L-18	Upstream "V" Cluster	Very Low	1	3	9.4	1%	30%	1%
L-19	Downstream "V" Cluster	High	4	12	4.7	3%	35%	4%
L-20	Downstream "V" Cluster	High	4	12	9.4	3%	27%	3%
L-21	Downstream "V" Cluster	Medium	3	9	4.7	2%	37%	3%

Test #	Config	Density	# Clusters	# Boulders	Flow (cfs)	Plan View Area Blocked (%)	Average Cross-section Area Blocked (%)	Volume Blocked (%)
L-22	Downstream "V" Cluster	Medium	3	9	9.4	2%	28%	2%
L-23	Downstream "V" Cluster	Low	2	6	4.7	1%	42%	2%
L-24	Downstream "V" Cluster	Low	2	6	9.4	1%	29%	2%
L-25	Downstream "V" Cluster	Very Low	1	3	4.7	1%	44%	1%
L-26	Downstream "V" Cluster	Very Low	1	3	9.4	1%	29%	1%
L-27	Diamond Cluster	High	4	16	4.7	4%	29%	5%
L-28	Diamond Cluster	High	4	16	9.4	4%	24%	4%
L-29	Diamond Cluster	Medium	3	12	4.7	3%	33%	4%
L-30	Diamond Cluster	Medium	3	12	9.4	3%	25%	3%
L-31	Diamond Cluster	Low	2	8	4.7	2%	44%	3%
L-32	Diamond Cluster	Low	2	8	9.4	2%	26%	2%
S-1	Single	Medium	4	4		1%	11%	
S-2	Single	Medium	4	4	2.3	1%	7%	1%
S-3	Single	Medium	4	4	4.7	0%	3%	1%
S-4	Single	Med-High	6	6	9.4	1%	10%	0%
S-5	Single	Med-High	6	6	2.3	1%	6%	1%
S-6	Single	Med-High	6	6	4.7	1%	3%	1%
S-7	Single	High	8	8	9.4	2%	10%	0%
S-8	Single	High	8	8	2.3	1%	6%	2%
S-9	Single	High	8	8	4.7	1%	3%	1%
S-10	Single	Low	2	2	9.4	0%	10%	1%
S-11	Single	Low	2	2	2.3	0%	7%	0%
S-12	Single	Low	2	2	4.7	0%	3%	0%
S-13	Single	Very Low	1	1	9.4	0%	10%	0%
S-14	Single	Very Low	1	1	2.3	0%	8%	0%

Test #	Config	Density	# Clusters	# Boulders	Flow (cfs)	Plan View Area Blocked (%)	Average Cross-section Area Blocked (%)	Volume Blocked (%)
S-15	Single	Very Low	1	1	4.7	0%	4%	0%
S-16	Upstream "V" Cluster	High	4	12	9.4	2%	25%	0%
S-17	Upstream "V" Cluster	High	4	12	2.3	2%	17%	2%
S-18	Upstream "V" Cluster	High	4	12	4.7	1%	17%	1%
S-19	Upstream "V" Cluster	Medium	3	9	9.4	2%	27%	1%
S-20	Upstream "V" Cluster	Medium	3	9	2.3	2%	18%	2%
S-21	Upstream "V" Cluster	Medium	3	9	4.7	1%	9%	1%
S-22	Upstream "V" Cluster	Low	2	6	9.4	1%	26%	1%
S-23	Upstream "V" Cluster	Low	2	6	2.3	1%	18%	1%
S-24	Upstream "V" Cluster	Low	2	6	4.7	1%	9%	1%
S-25	Upstream "V" Cluster	Very Low	1	3	9.4	1%	36%	0%
S-26	Upstream "V" Cluster	Very Low	1	3	2.3	1%	21%	1%
S-27	Upstream "V" Cluster	Very Low	1	3	4.7	0%	11%	0%
S-28	Downstream "V" Cluster	High	4	12	9.4	2%	28%	0%
S-29	Downstream "V" Cluster	High	4	12	2.3	2%	17%	2%
S-30	Downstream "V" Cluster	High	4	12	4.7	1%	9%	1%
S-31	Downstream "V" Cluster	Medium	3	9	9.4	2%	26%	1%
S-32	Downstream "V" Cluster	Medium	3	9	2.3	1%	16%	2%
S-33	Downstream "V" Cluster	Medium	3	9	4.7	1%	10%	1%
S-34	Downstream "V" Cluster	Low	2	6	9.4	1%	27%	1%

Test #	Config	Density	# Clusters	# Boulders	Flow (cfs)	Plan View Area Blocked (%)	Average Cross-section Area Blocked (%)	Volume Blocked (%)
S-35	Downstream "V" Cluster	Low	2	6	2.3	1%	18%	1%
S-36	Downstream "V" Cluster	Low	2	6	4.7	1%	9%	1%
S-37	Downstream "V" Cluster	Very Low	1	3	9.4	1%	30%	0%
S-38	Downstream "V" Cluster	Very Low	1	3	2.3	0%	18%	1%
S-39	Downstream "V" Cluster	Very Low	1	3	4.7	0%	11%	0%

Table A- 4 Test configurations and boulder properties for small rocks. Please see Analysis Methods for a comprehensive definition of variables.

Test Number	Configuration	Density	Clusters Used	Number of Clusters	Number of Boulders	A_{P-BCT} (ft^2)	A_{XS-BCT} (ft^2)	VOL_{BCT} (ft^3)	Flow (cfs)
S-1	Single	Medium	1:4	4	4	1.3	0.8	0.4	2.3
S-2	Single	Medium	1:4	4	4	1.3	0.8	0.4	4.7
S-3	Single	Medium	1:4	4	4	1.3	0.8	0.4	9.4
S-4	Single	Med-High	1:6	6	6	1.9	1.1	0.6	2.3
S-5	Single	Med-High	1:6	6	6	1.9	1.1	0.6	4.7
S-6	Single	Med-High	1:6	6	6	1.9	1.1	0.6	9.4
S-7	Single	High	1:8	8	8	2.6	1.5	0.8	2.3
S-8	Single	High	1:8	8	8	2.6	1.5	0.8	4.7
S-9	Single	High	1:8	8	8	2.6	1.5	0.8	9.4
S-10	Single	Low	2, 4	2	2	0.7	0.4	0.2	2.3
S-11	Single	Low	2, 4	2	2	0.7	0.4	0.2	4.7
S-12	Single	Low	2, 4	2	2	0.7	0.4	0.2	9.4
S-13	Single	Very Low	2	1	1	0.3	0.2	0.1	2.3
S-14	Single	Very Low	2	1	1	0.3	0.2	0.1	4.7
S-15	Single	Very Low	2	1	1	0.3	0.2	0.1	9.4

Test Number	Configuration	Density	Clusters Used	Number of Clusters	Number of Boulders	A_{P-BCT} (ft^2)	A_{XS-BCT} (ft^2)	VOL_{BCT} (ft^3)	Flow (cfs)
S-16	Upstream "V" Cluster	High	1, 2, 3, 4	4	12	3.8	2.2	1.2	2.3
S-17	Upstream "V" Cluster	High	1, 2, 3, 4	4	12	3.8	2.2	1.2	4.7
S-18	Upstream "V" Cluster	High	1, 2, 3, 4	4	12	3.8	2.2	1.2	9.4
S-19	Upstream "V" Cluster	Medium	2, 3, 4	3	9	2.9	1.6	0.9	2.3
S-20	Upstream "V" Cluster	Medium	2, 3, 4	3	9	2.9	1.6	0.9	4.7
S-21	Upstream "V" Cluster	Medium	2, 3, 4	3	9	2.9	1.6	0.9	9.4
S-22	Upstream "V" Cluster	Low	2, 4	2	6	1.9	1.1	0.6	2.3
S-23	Upstream "V" Cluster	Low	2, 4	2	6	1.9	1.1	0.6	4.7
S-24	Upstream "V" Cluster	Low	2, 4	2	6	1.9	1.1	0.6	9.4
S-25	Upstream "V" Cluster	Very Low	2	1	3	1.0	0.6	0.3	2.3
S-26	Upstream "V" Cluster	Very Low	2	1	3	1.0	0.6	0.3	4.7
S-27	Upstream "V" Cluster	Very Low	2	1	3	1.0	0.6	0.3	9.4
S-28	Downstream "V" Cluster	High	1, 2, 3, 4	4	12	3.8	2.2	1.2	2.3
S-29	Downstream "V" Cluster	High	1, 2, 3, 4	4	12	3.8	2.2	1.2	4.7
S-30	Downstream "V" Cluster	High	1, 2, 3, 4	4	12	3.8	2.2	1.2	9.4
S-31	Downstream "V" Cluster	Medium	2, 3, 4	3	9	2.9	1.6	0.9	2.3
S-32	Downstream "V" Cluster	Medium	2, 3, 4	3	9	2.9	1.6	0.9	4.7
S-33	Downstream "V" Cluster	Medium	2, 3, 4	3	9	2.9	1.6	0.9	9.4
S-34	Downstream "V" Cluster	Low	2, 4	2	6	1.9	1.1	0.6	2.3
S-35	Downstream "V" Cluster	Low	2, 4	2	6	1.9	1.1	0.6	4.7
S-36	Downstream "V" Cluster	Low	2, 4	2	6	1.9	1.1	0.6	9.4
S-37	Downstream "V" Cluster	Very Low	2	1	3	1.0	0.6	0.3	2.3
S-38	Downstream "V" Cluster	Very Low	2	1	3	1.0	0.6	0.3	4.7
S-39	Downstream "V" Cluster	Very Low	2	1	3	1.0	0.6	0.3	9.4

Table A- 5 Flow Properties per large rock test. Please see Analysis Methods for a comprehensive definition of variables.

Config	Density	Flow (cfs)	L_X (ft)	$\overline{Z_B}$ (ft)	$\overline{W}$ (ft)	$\overline{Y}$ (ft)	$A_{P\text{-}Flow}$ (ft^2)	VOL_{Flow} (ft^3)	$\overline{Y_{US}} / \overline{Z_B}$ (-)	$\overline{\%A_{XS-Blocked}}$ (-)	$\%A_{XS\text{-}Blocked\text{-}Total}$ (-)
Baseline	N/A	2.3	26	-	5.6	0.3	146	44	-	0%	0%
Baseline	N/A	4.7	26	-	7	0.34	182	62	-	0%	0%
Baseline	N/A	9.4	26	-	11	0.44	286	126	-	0%	0%
Single	Medium	4.7	26	0.64	9.46	0.43	246	105	0.67	16%	6%
Single	Medium	9.4	26	0.64	11.00	0.51	286	147	0.80	11%	4%
Single	Med-High	4.7	26	0.64	9.24	0.42	240	102	0.81	17%	9%
Single	Med-High	9.4	26	0.64	11.00	0.55	286	156	1.02	11%	6%
Single	High	4.7	26	0.64	9.13	0.43	237	102	0.81	16%	11%
Single	High	9.4	26	0.64	11.00	0.57	286	164	1.01	10%	7%
Single	Low	4.7	26	0.58	8.83	0.40	230	91	0.75	17%	3%
Single	Low	9.4	26	0.58	11.00	0.49	286	141	0.99	11%	2%
Single	Very Low	4.7	26	0.60	10.25	0.38	267	102	0.61	16%	2%
Single	Very Low	9.4	26	0.60	11.00	0.47	286	134	0.99	12%	1%
Upstream "V"	High	4.7	26	2.64	10.73	0.45	279	126	0.19	42%	25%
Upstream "V"	High	9.4	26	2.64	11.00	0.56	286	161	0.25	33%	20%
Upstream "V"	Medium	4.7	26	2.65	10.53	0.45	274	123	0.19	42%	19%
Upstream "V"	Medium	9.4	26	2.65	11.00	0.55	286	157	0.25	33%	15%
Upstream "V"	Low	4.7	26	2.67	8.54	0.39	222	87	0.16	55%	17%
Upstream "V" Cluster	Low	9.4	26	2.67	11.00	0.51	286	145	0.22	33%	10%
Upstream "V" Cluster	Very Low	4.7	26	2.54	10.42	0.37	271	100	0.16	45%	7%
Upstream "V" Cluster	Very Low	9.4	26	2.54	11.00	0.46	286	132	0.21	36%	5%
Downstream "V"	High	4.7	26	2.64	10.71	0.44	278	123	0.20	43%	26%
Downstream "V"	High	9.4	26	2.64	11.00	0.56	286	159	0.26	34%	20%
Downstream "V"	Medium	4.7	26	2.65	10.61	0.42	276	116	0.20	44%	20%
Downstream "V"	Medium	9.4	26	2.65	11.00	0.53	286	152	0.25	34%	15%

Config	Density	Flow (cfs)	L_X (ft)	$\overline{Z_B}$ (ft)	$\overline{W}$ (ft)	$\overline{Y}$ (ft)	$A_{P\text{-}Flow}$ (ft^2)	VOL_{Flow} (ft^3)	$\overline{Y_{US}/Z_B}$ (-)	$\overline{\%A_{XS-Blocked}}$ (-)	$\%A_{XS\text{-}Blocked\text{-}Total}$ (-)
Downstream "V"	Low	4.7	26	2.67	10.00	0.38	260	99	0.18	48%	15%
Downstream "V"	Low	9.4	26	2.67	11.00	0.50	286	144	0.23	33%	10%
Downstream "V"	Very Low	4.7	26	2.54	10.42	0.33	271	90	0.17	53%	8%
Downstream "V" Cluster	Very Low	9.4	26	2.54	11.00	0.47	286	136	0.23	35%	5%
Diamond	High	4.7	26	2.64	10.73	0.49	279	136	0.20	39%	25%
Diamond	High	9.4	26	2.64	11.00	0.59	286	170	0.26	31%	20%
Diamond	Medium	4.7	26	2.65	10.53	0.44	274	120	0.19	43%	21%
Diamond	Medium	9.4	26	2.65	11.00	0.56	286	161	0.25	32%	16%
Diamond	Low	4.7	26	2.67	8.54	0.39	222	86	0.18	56%	17%
Diamond	Low	9.4	26	2.67	11.00	0.51	286	146	0.22	33%	10%

Table A- 6 Flow Properties per small rock test. Please see Analysis Methods for a comprehensive definition of variables.

Config	Density	Flow (cfs)	L_X (ft)	$\overline{Z_B}$ (ft)	$\overline{W}$ (ft)	$\overline{Y}$ (ft)	$A_{P\text{-}Flow}$ (ft^2)	VOL_{Flow} (ft^3)	$\overline{Y_{US}/Z_B}$ (-)	$\overline{\%A_{XS-Blocked}}$ (-)	$\%A_{XS\text{-}Blocked\text{-}Total}$ (-)
Single	Medium	2.3	26	0.35	5.94	0.31	154	48	0.89	11%	2%
Single	Medium	4.7	26	0.35	7.13	0.41	185	76	1.05	7%	1%
Single	Medium	9.4	26	0.35	11.00	0.54	286	155	1.54	3%	3%
Single	Med-High	2.3	26	0.32	5.97	0.33	155	52	1.03	10%	3%
Single	Med-High	4.7	26	0.32	7.28	0.42	189	79	1.23	6%	2%
Single	Med-High	9.4	26	0.32	11.00	0.55	286	157	1.69	3%	1%
Single	High	2.3	26	0.31	6.00	0.32	156	49	1.00	10%	4%
Single	High	4.7	26	0.31	7.45	0.41	194	79	1.27	6%	3%
Single	High	9.4	26	0.31	11.00	0.52	286	147	1.69	3%	1%
Single	Low	2.3	26	0.34	5.46	0.35	142	50	1.04	10%	1%
Single	Low	4.7	26	0.34	7.08	0.37	184	69	1.07	7%	1%
Single	Low	9.4	26	0.34	11.00	0.54	286	156	1.37	3%	0.3%
Single	Very Low	2.3	26	0.40	6.00	0.35	156	55	0.88	10%	1%
Single	Very Low	4.7	26	0.40	7.00	0.37	182	68	0.78	8%	0.5%
Single	Very Low	9.4	26	0.40	11.00	0.49	286	139	1.21	4%	0.2%
Upstream "V"	High	2.3	26	0.32	6.19	0.35	161	57	1.11	25%	8%
Upstream "V"	High	4.7	26	0.32	7.83	0.41	204	84	1.35	17%	6%
Upstream "V"	High	9.4	26	0.32	11.00	0.52	286	149	1.76	17%	3%
Upstream "V"	Medium	2.3	26	0.32	5.86	0.35	152	53	1.10	27%	7%
Upstream "V"	Medium	4.7	26	0.32	7.36	0.40	191	76	1.32	19%	5%
Upstream "V"	Medium	9.4	26	0.32	11.00	0.53	286	151	1.66	9%	2%
Upstream "V"	Low	2.3	26	0.31	5.67	0.37	147	55	1.18	27%	4%
Upstream "V"	Low	4.7	26	0.31	7.17	0.38	186	70	1.15	18%	3%
Upstream "V"	Low	9.4	26	0.31	11.00	0.52	286	150	1.71	9%	1%
Upstream "V"	Very Low	2.3	26	0.34	5.75	0.28	150	41	0.81	36%	3%
Upstream "V"	Very Low	4.7	26	0.34	7.33	0.37	191	71	1.15	21%	2%

Config	Density	Flow (cfs)	L_X (ft)	$\overline{Z_B}$ (ft)	$\overline{W}$ (ft)	$\overline{Y}$ (ft)	$A_{P\text{-}Flow}$ (ft^2)	VOL_{Flow} (ft^3)	$\overline{Y_{US}}/\overline{Z_B}$ (-)	$\overline{\%A_{XS-Blocked}}$ (-)	$\%A_{XS\text{-}Blocked\text{-}Total}$ (-)
Upstream "V"	Very Low	9.4	26	0.34	11.00	0.48	286	136	1.48	11%	1%
Downstream "V"	High	2.3	26	0.32	6.04	0.32	157	51	1.02	28%	9%
Downstream "V"	High	4.7	26	0.32	8.54	0.40	222	90	1.22	17%	5%
Downstream "V"	High	9.4	26	0.32	11.00	0.52	286	150	1.65	9%	3%
Downstream "V"	Medium	2.3	26	0.32	6.22	0.34	162	55	1.07	26%	6%
Downstream "V"	Medium	4.7	26	0.32	8.08	0.41	210	85	1.20	17%	4%
Downstream "V"	Medium	9.4	26	0.32	11.00	0.52	286	147	1.56	10%	2%
Downstream "V"	Low	2.3	26	0.31	5.46	0.36	142	50	1.13	28%	4%
Downstream "V"	Low	4.7	26	0.31	8.33	0.35	217	76	1.13	18%	3%
Downstream "V"	Low	9.4	26	0.31	11.00	0.52	286	147	1.55	10%	1%
Downstream "V"	Very Low	2.3	26	0.34	6.08	0.31	158	49	0.91	30%	2%
Downstream "V"	Very Low	4.7	26	0.34	8.08	0.38	210	80	1.16	18%	1%
Downstream "V"	Very Low	9.4	26	0.34	11.00	0.46	286	132	1.43	11%	1%

Appendix B: Water Surface Elevations

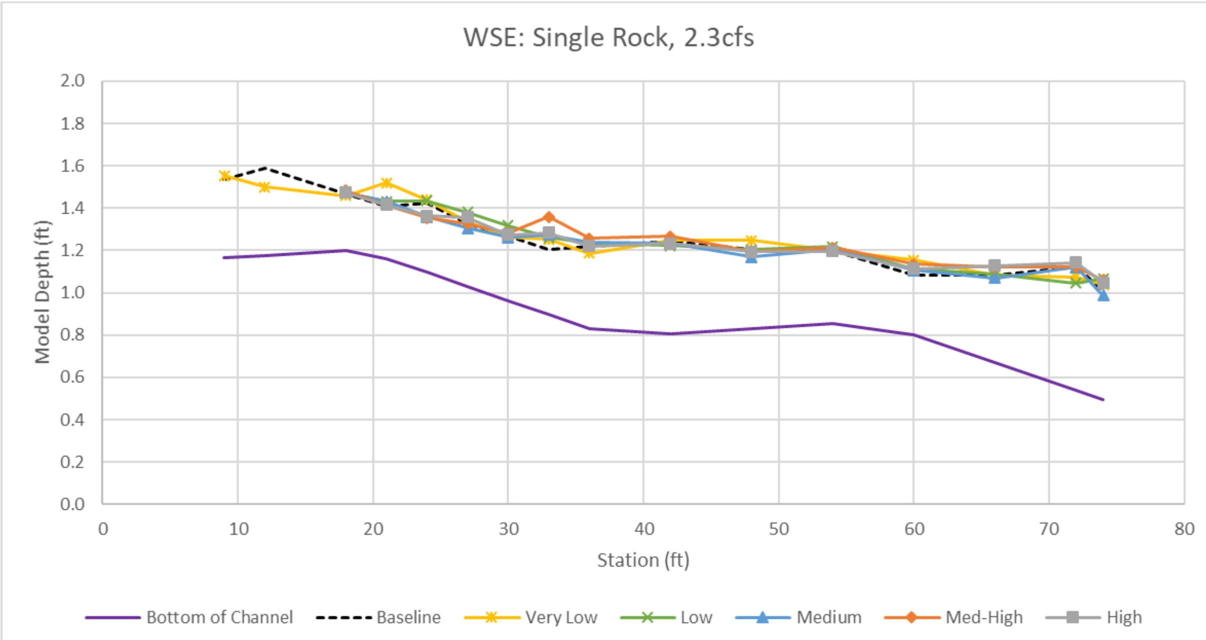

Figure B- 1 Water surface and channel invert profiles for small rock, single rock configurations at 2.3 cfs.

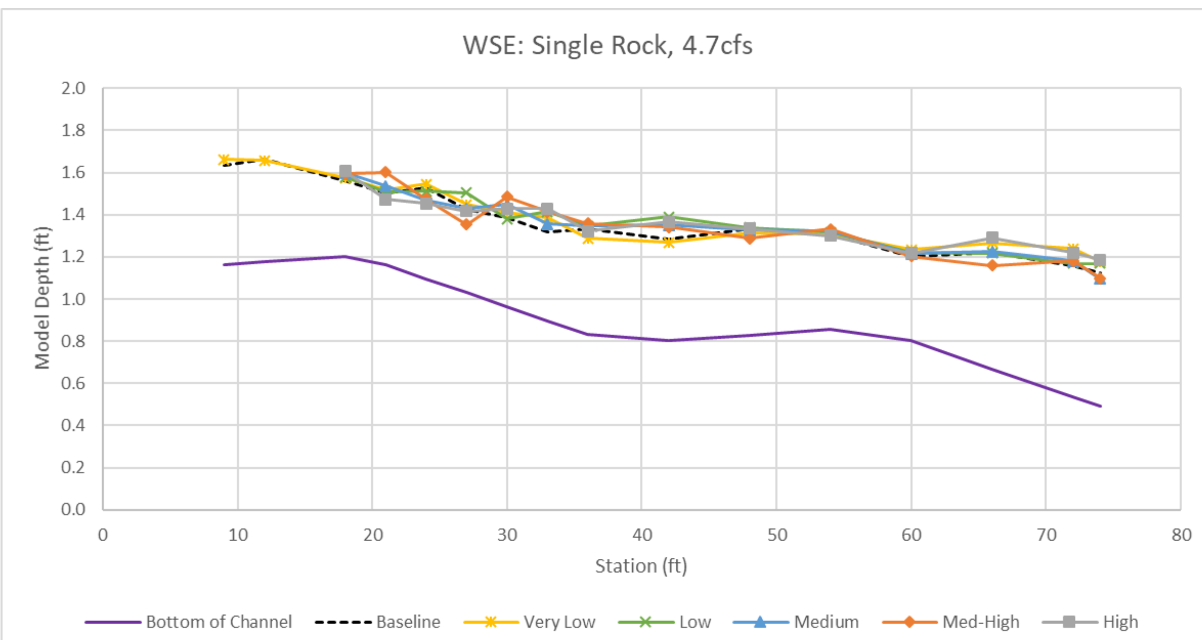

Figure B- 2 Water surface and channel invert profiles for small rock, single rock configurations at 4.7 cfs.

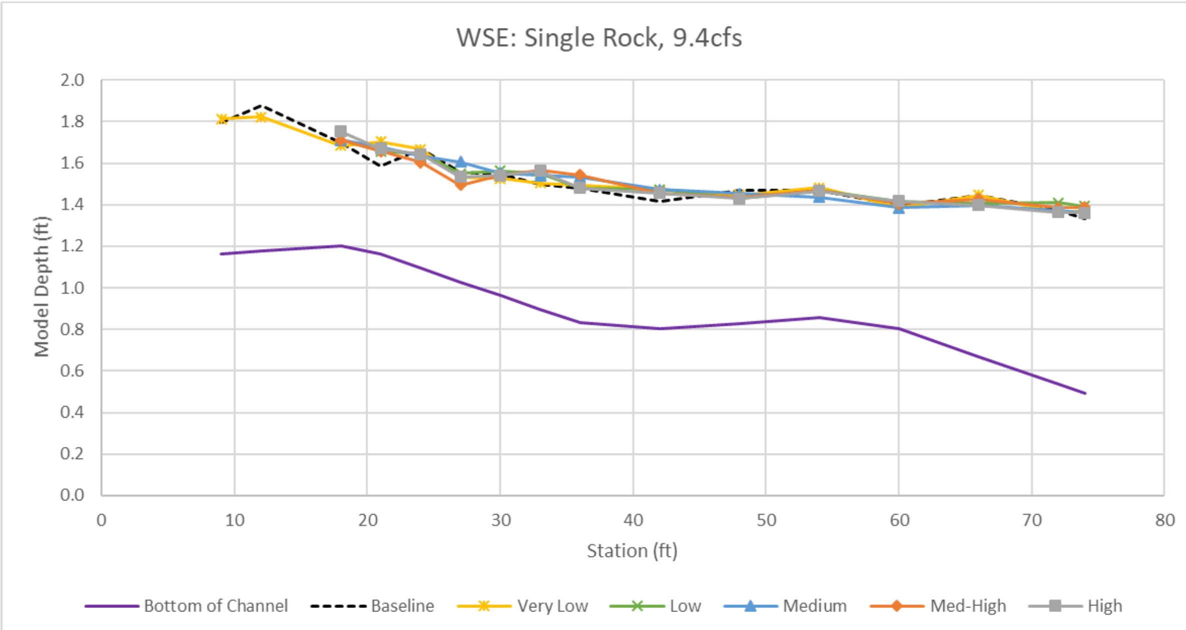

Figure B- 3 Water surface and channel invert profiles for small rock, single rock configurations at 9.4 cfs.

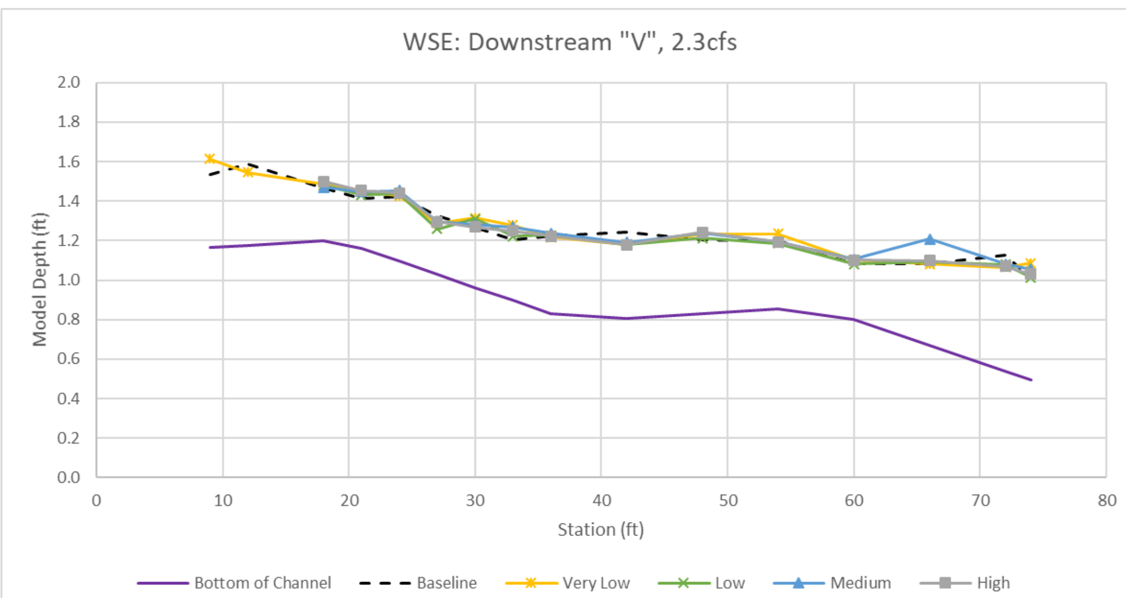

Figure B- 4 Water surface and channel invert profiles for small rock, Downstream “V” configurations at 2.3 cfs.

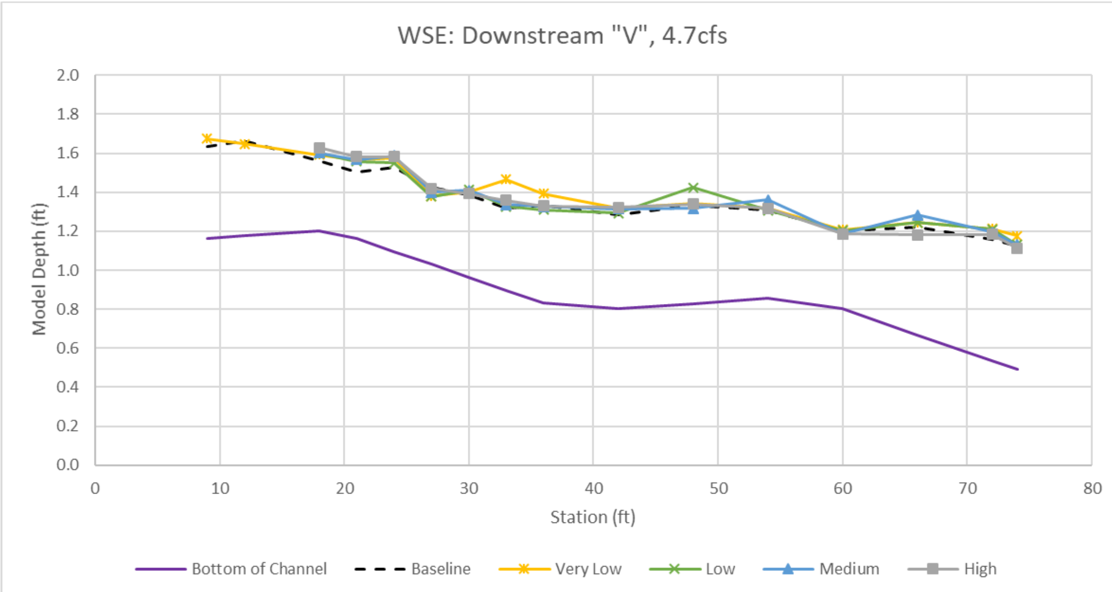

Figure B- 5 Water surface and channel invert profiles for small rock, Downstream "V" configurations at 4.7 cfs.

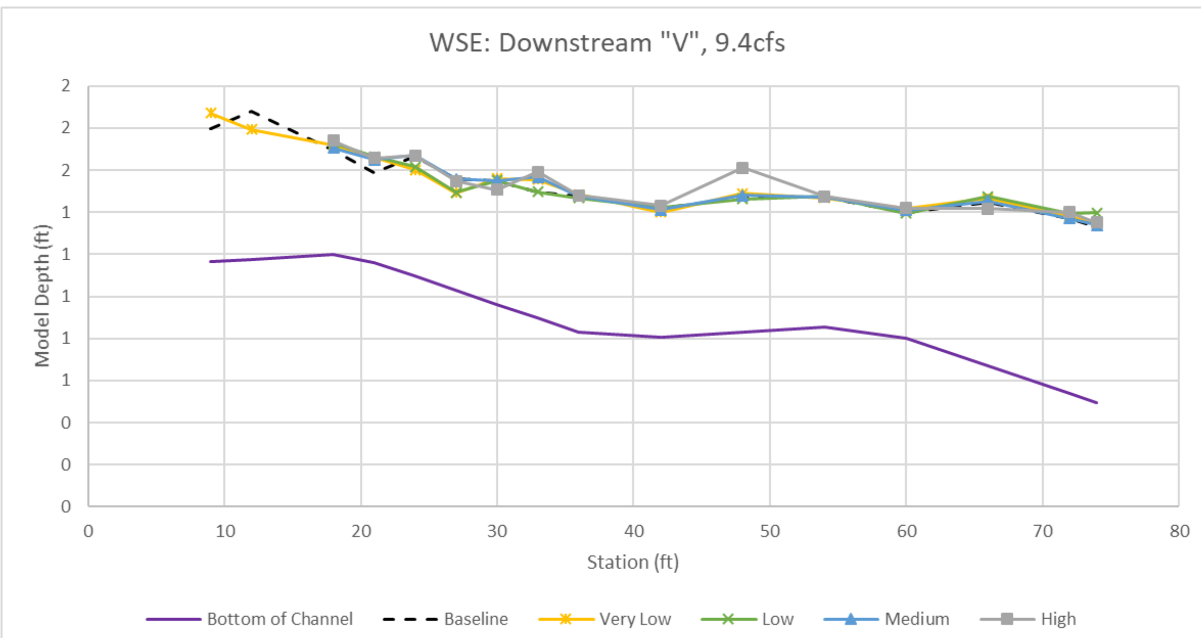

Figure B- 6 Water surface and channel invert profiles for small rock, Downstream "V" configurations at 9.4 cfs.

Appendix C: Velocity Distribution Curves (CDF)

Large Rocks

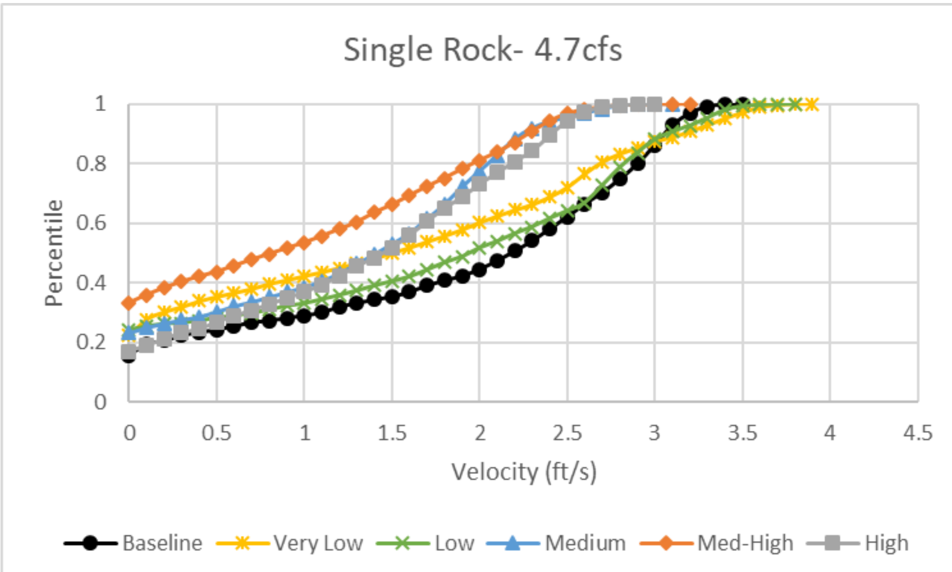

Figure C- 1 Large rock CDF curve for single rock configuration at 4.7 cfs.

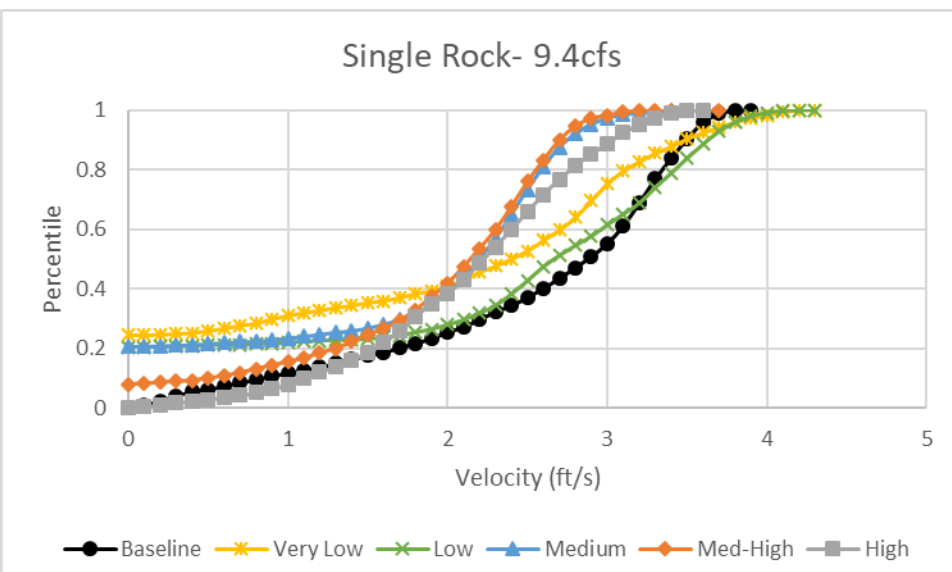

Figure C- 2 Large rock CDF curve for single rock configuration at 9.4 cfs.

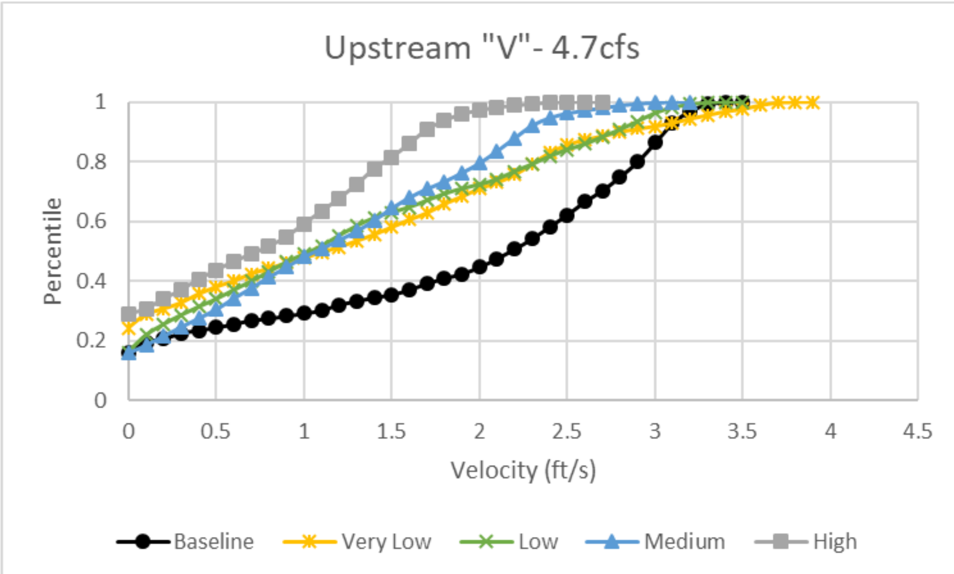

Figure C- 3 Large rock CDF curve for Upstream V configuration at 4.7 cfs.

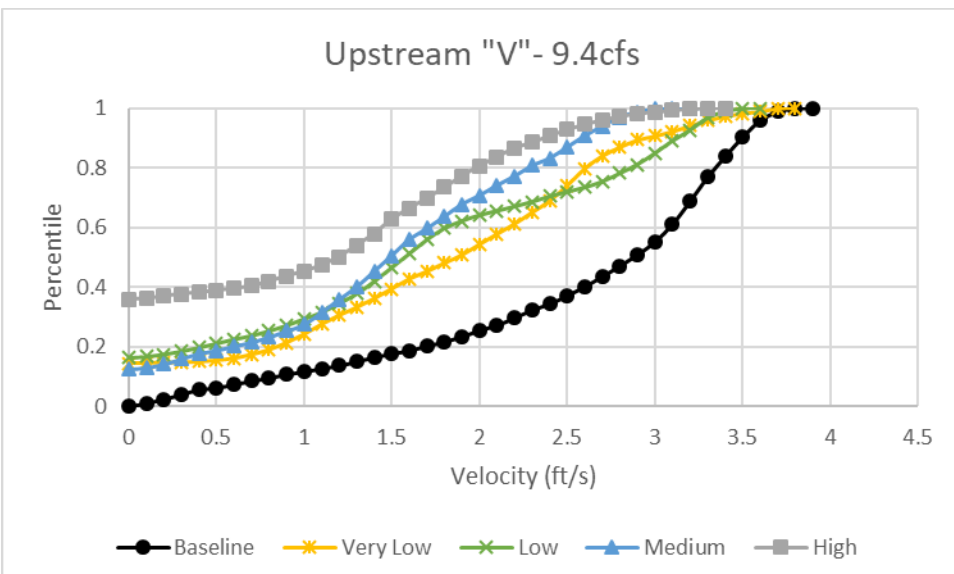

Figure C- 4 Large rock CDF curve for Upstream V configuration at 9.4 cfs.

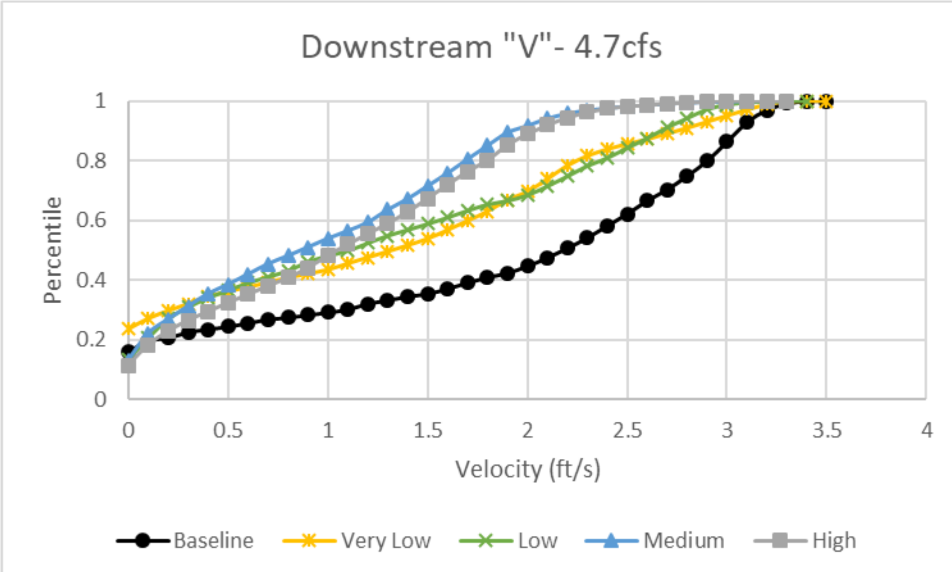

Figure C- 5 Large rock CDF curve for Downstream V configuration at 4.7 cfs.

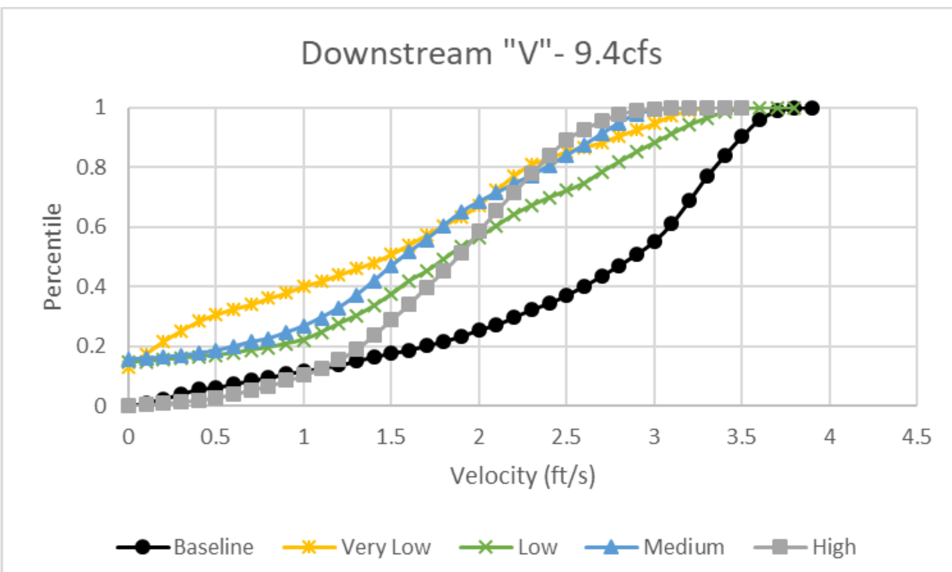

Figure C- 6 Large rock CDF curve for Downstream V configuration at 9.4 cfs.

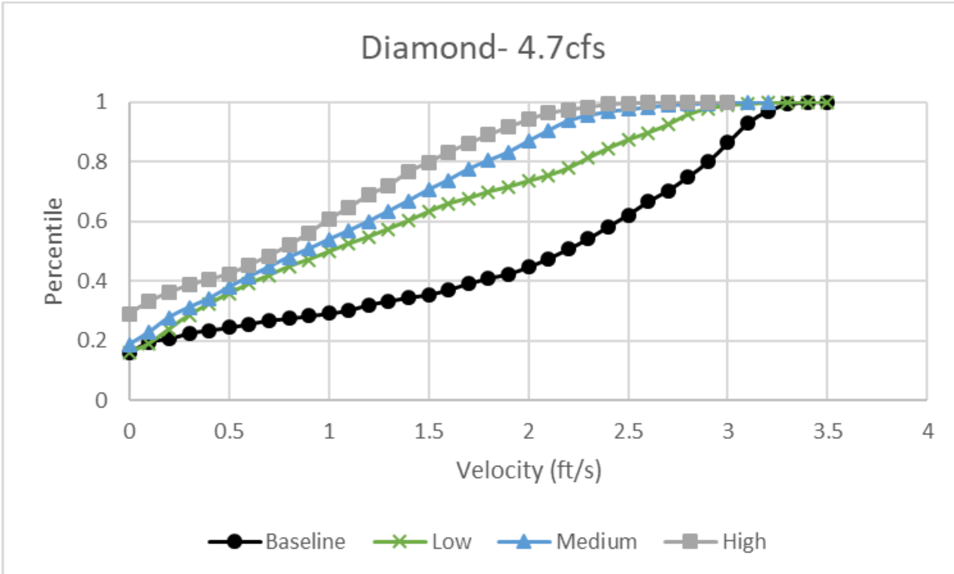

Figure C- 7 Large rock CDF curve for Diamond configuration at 9.4 cfs.

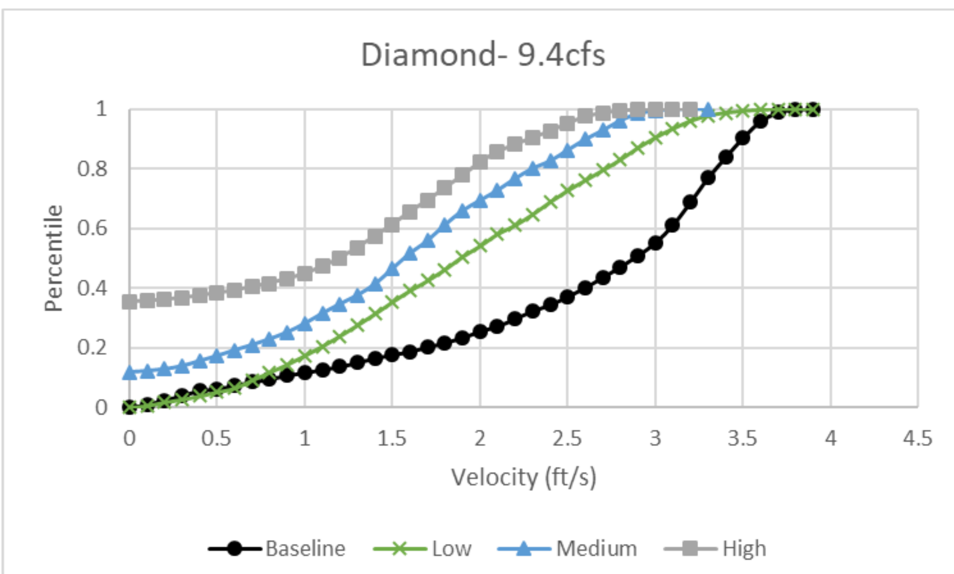

Figure C- 8 Large rock CDF curve for Diamond configuration at 9.4 cfs.

Small Rocks

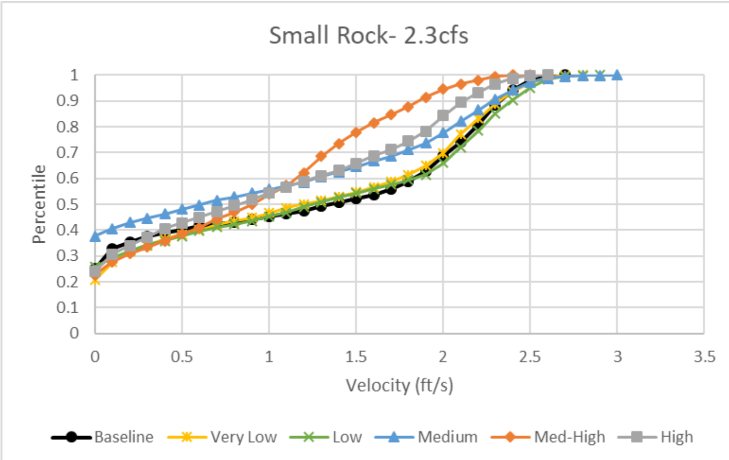

Figure C- 9 Small rock CDF curve for single rock configuration at 2.3 cfs.

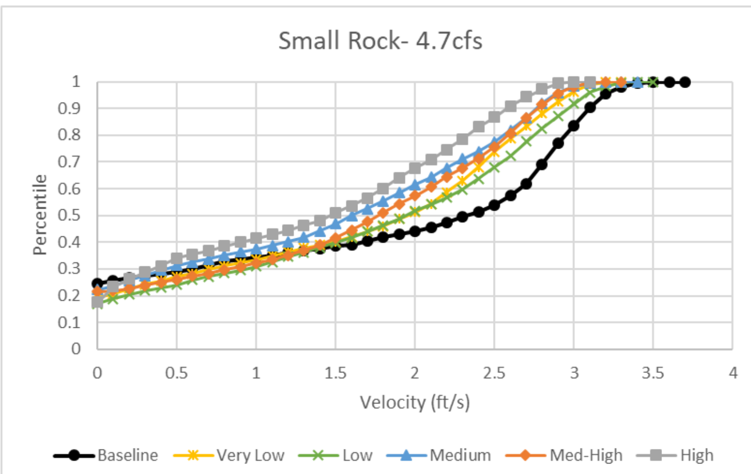

Figure C- 10 Small rock CDF curve for single rock configuration at 4.7 cfs.

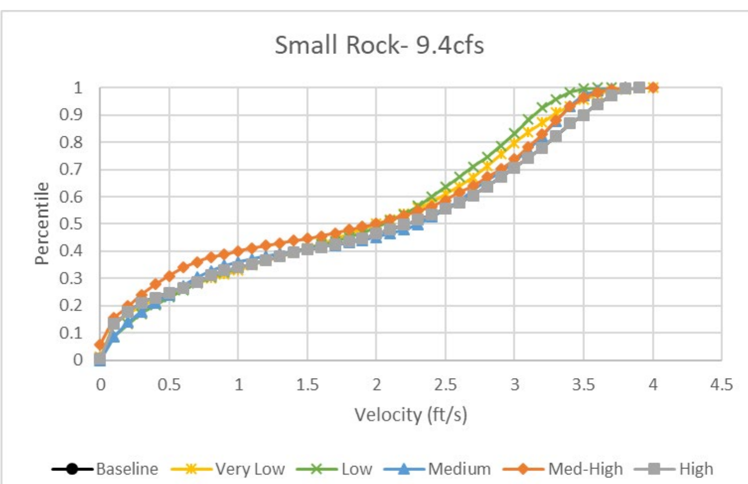

Figure C- 11 Small rock CDF curve for single rock configuration at 9.4 cfs.

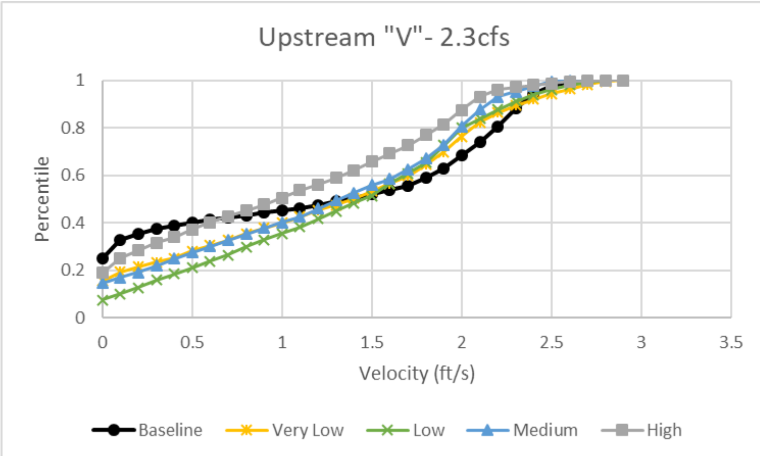

Figure C- 12 Small rock CDF curve for Upstream V configuration at 2.3 cfs.

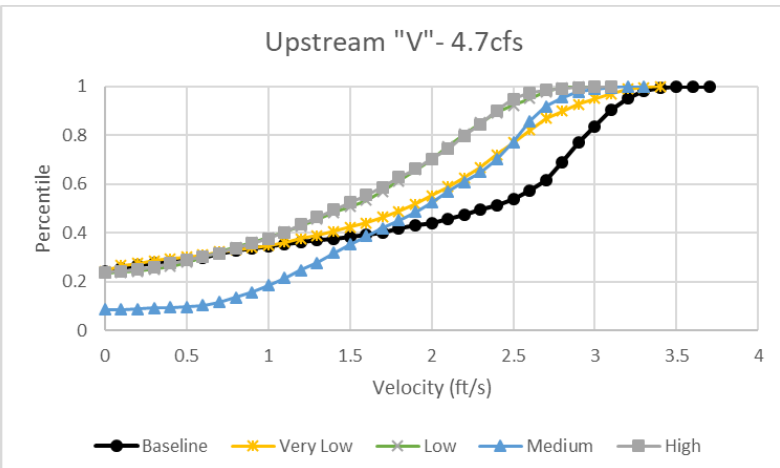

Figure C- 13 Small rock CDF curve for Upstream V configuration at 4.7 cfs.

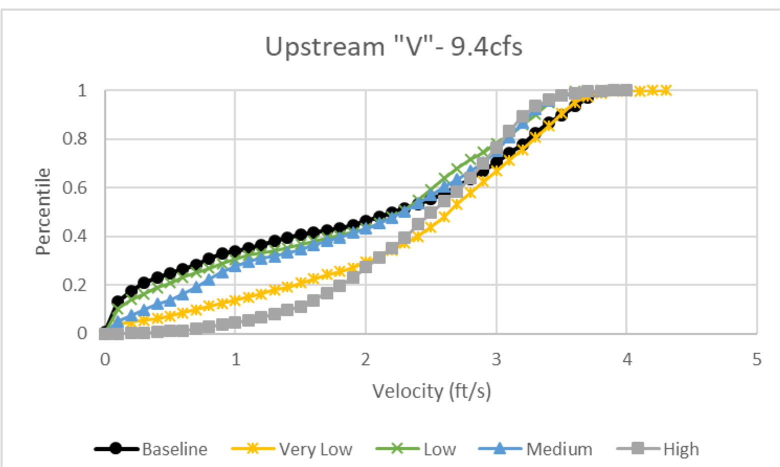

Figure C- 14 Small rock CDF curve for Upstream V configuration at 9.4 cfs.

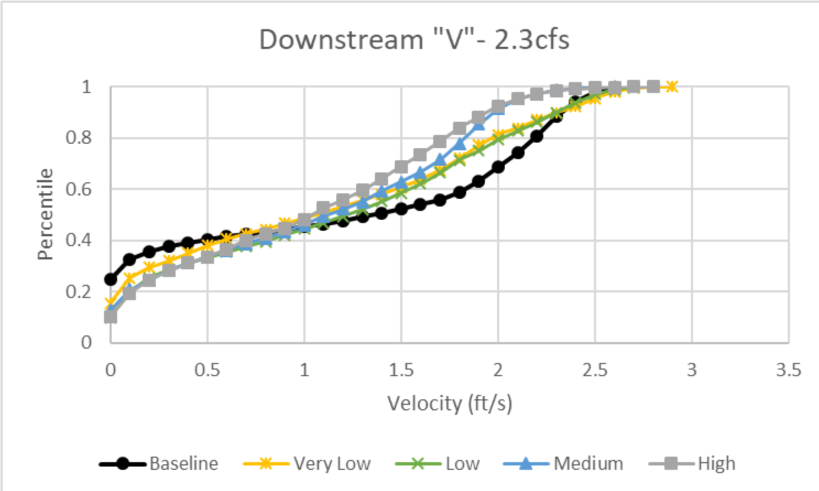

Figure C- 15 Small rock CDF curve for Downstream V configuration at 2.3 cfs.

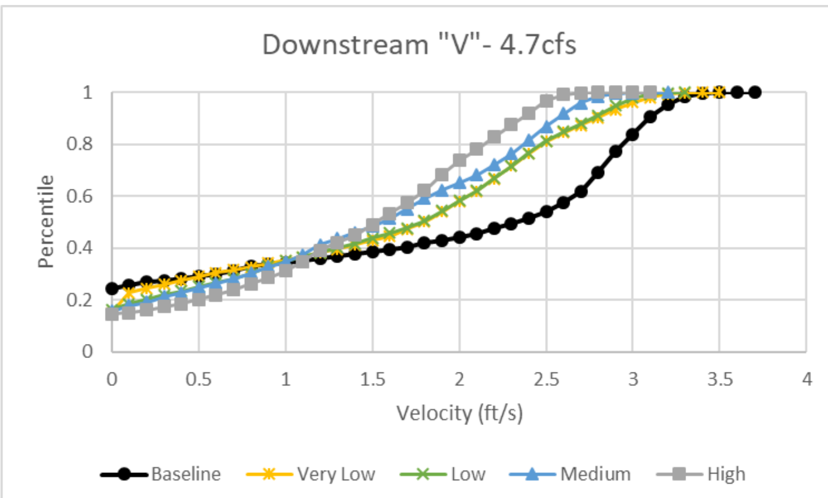

Figure C- 16 Small rock CDF curve for Downstream V configuration at 4.7 cfs.

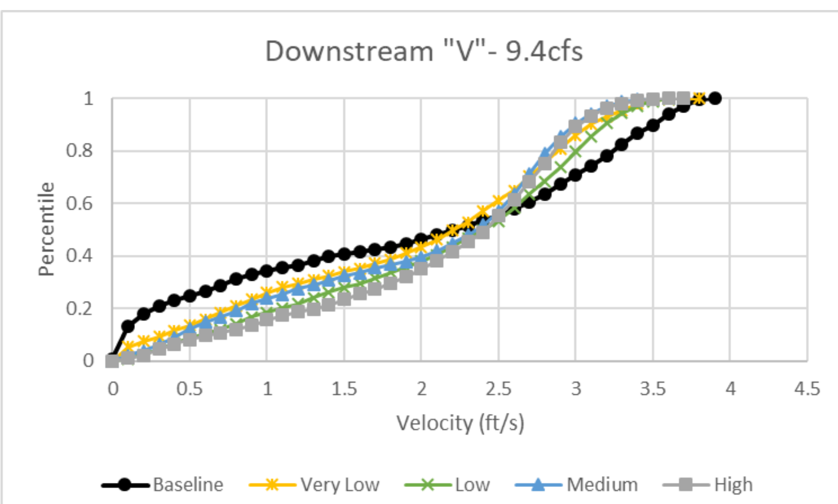

Figure C- 17 Small rock CDF curve for Downstream V configuration at 9.4 cfs.

Appendix D: Velocity Distribution Curves (PDF)

Plots in this appendix were originally developed with discharge and velocity values at prototype scale for a previous study. To convert the results to model scale, divide the velocity by a factor of 2.

Large Rocks

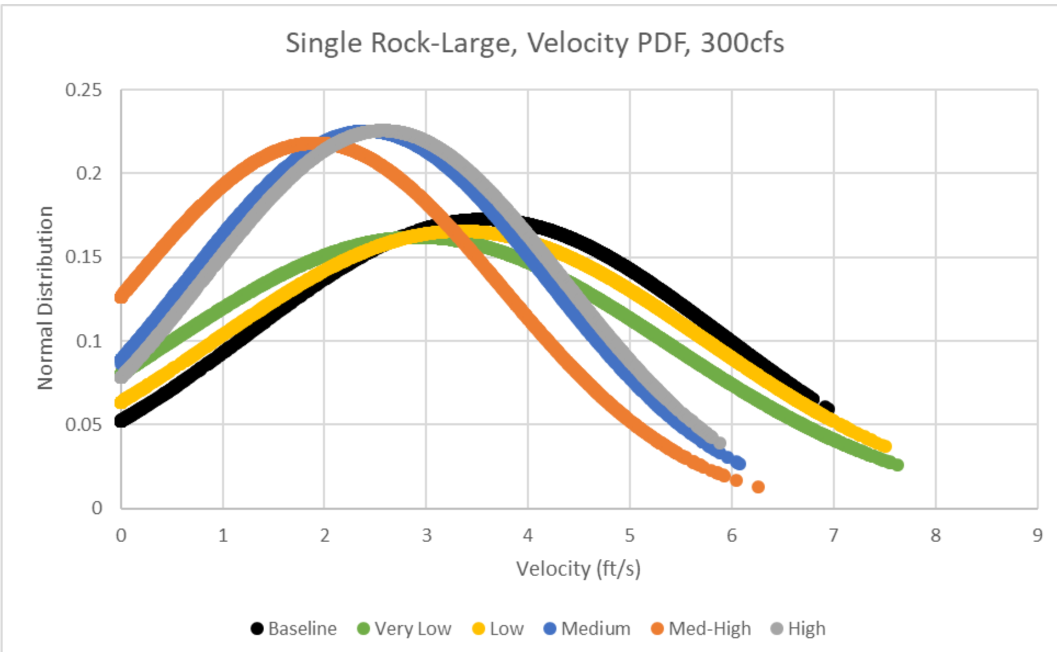

Figure D- 1 Large rock, single rock configuration velocity PDF curve at 300 cfs (4.7 cfs, laboratory scale).

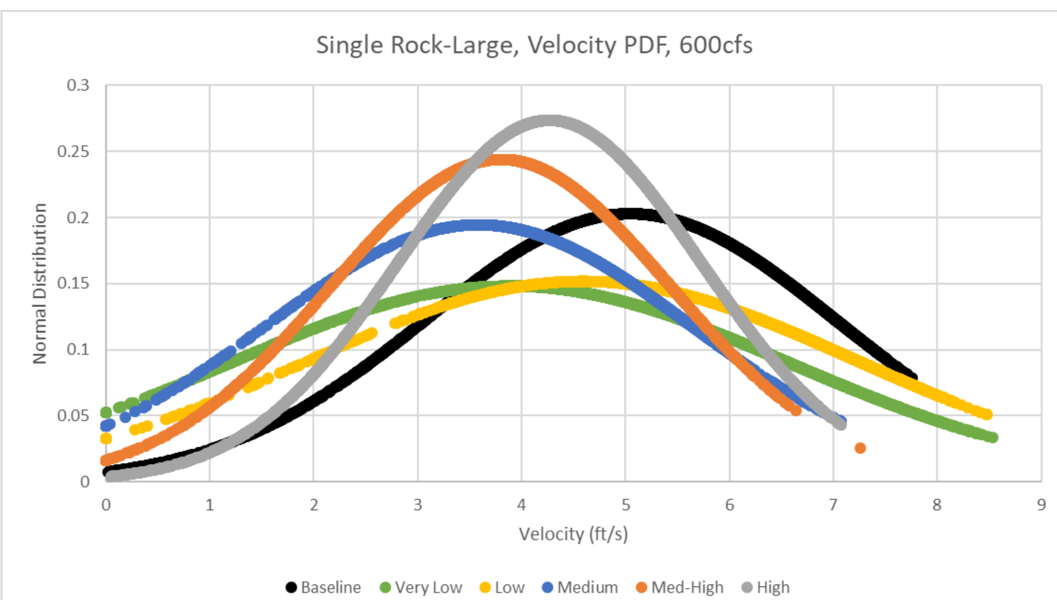

Figure D- 2 Large rock, single rock configuration velocity PDF curve at 600 cfs (9.4 cfs, laboratory scale).

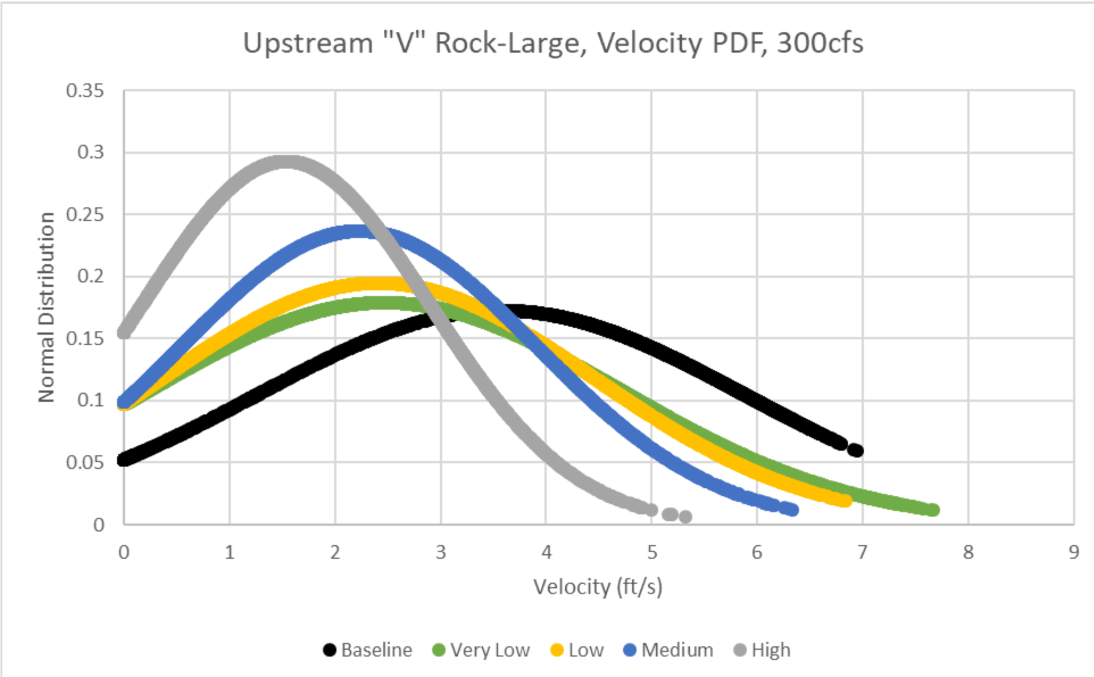

Figure D- 3 Large rock, Upstream V configuration velocity PDF curve at 300 cfs (4.7 cfs, laboratory scale).

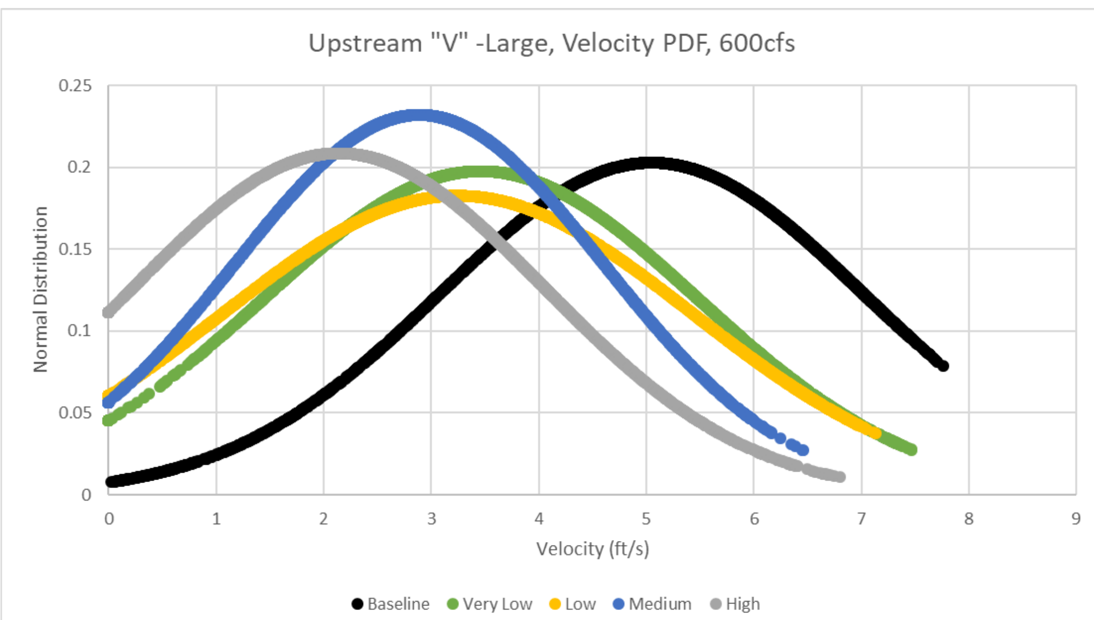

Figure D- 4 Large rock, Upstream V configuration velocity PDF curve at 600 cfs (9.4 cfs, laboratory scale).

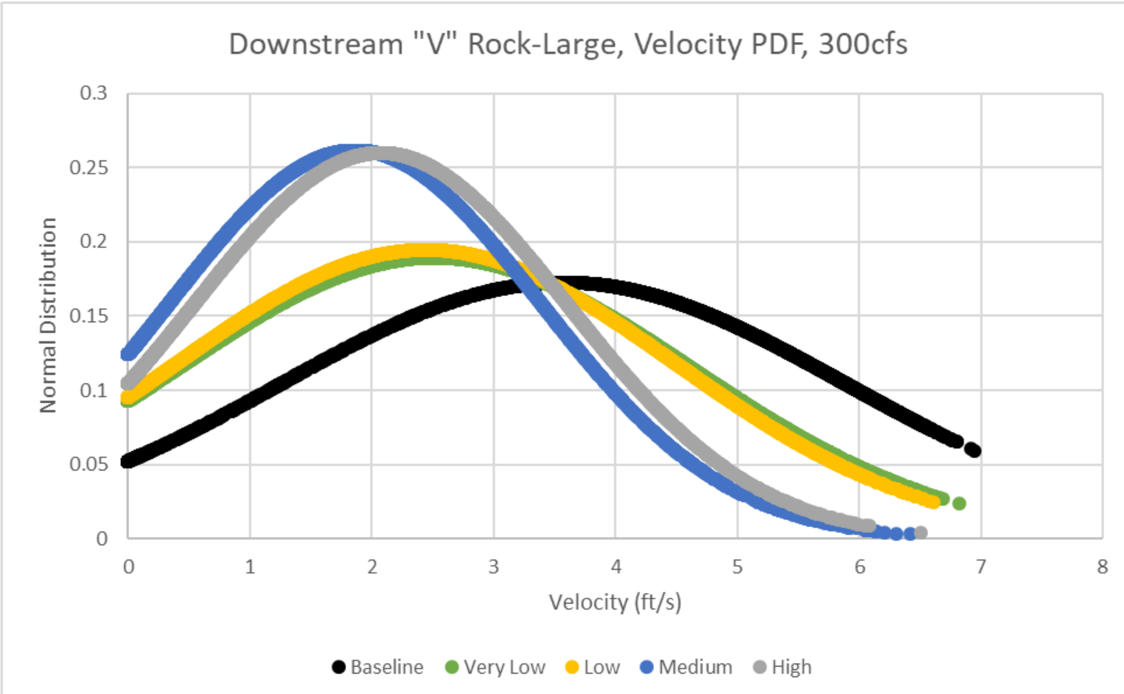

Figure D- 5 Large rock, Downstream V configuration velocity PDF curve at 300 cfs (4.7 cfs, laboratory scale).

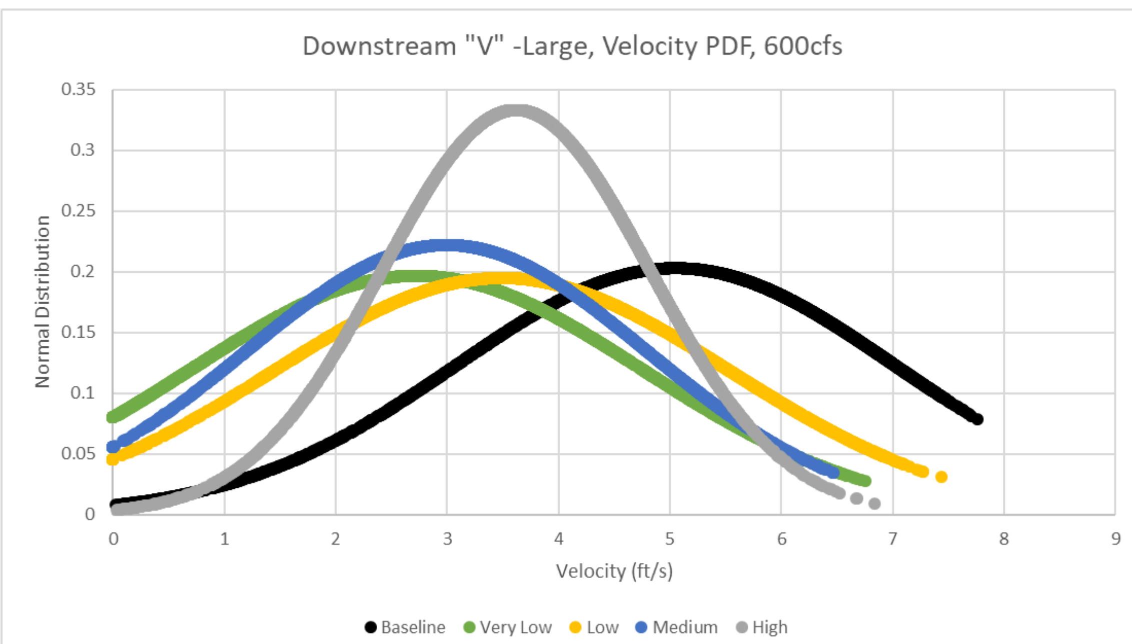

Figure D- 6 Large rock, Downstream V configuration velocity PDF curve at 600 cfs (9.4 cfs, laboratory scale).

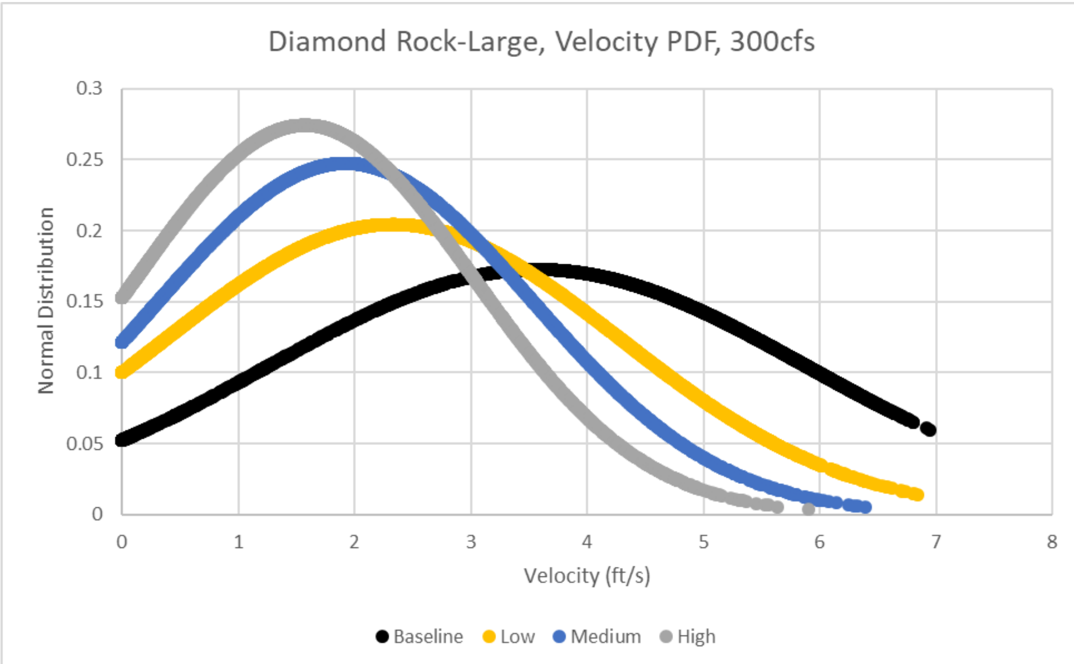

Figure D- 7 Large rock, Diamond configuration velocity PDF curve at 300 cfs (4.7 cfs, laboratory scale).

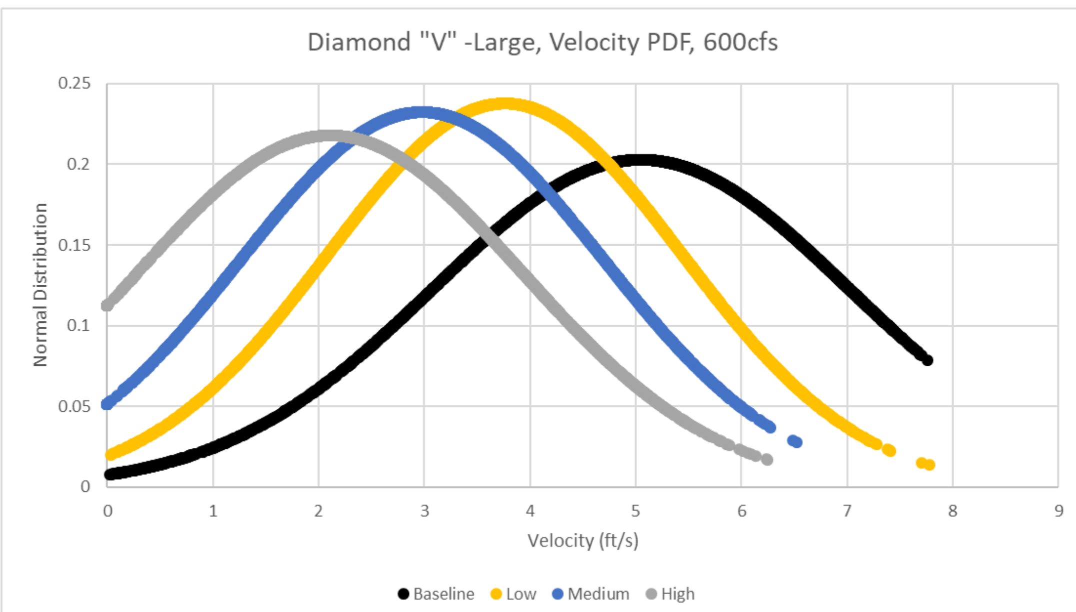

Figure D- 8 Large rock, Diamond configuration velocity PDF curve at 600 cfs (9.4 cfs, laboratory scale).

Small Rocks

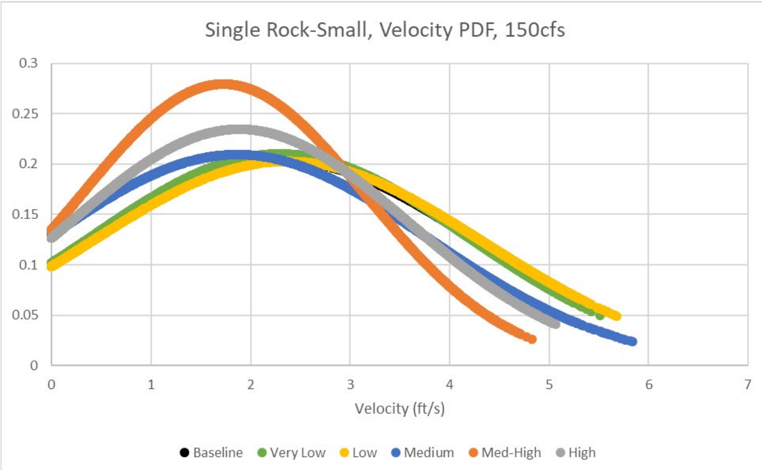

Figure D- 9 Small rock, single rock configuration velocity PDF curve at 150 cfs (2.3 cfs, laboratory scale).

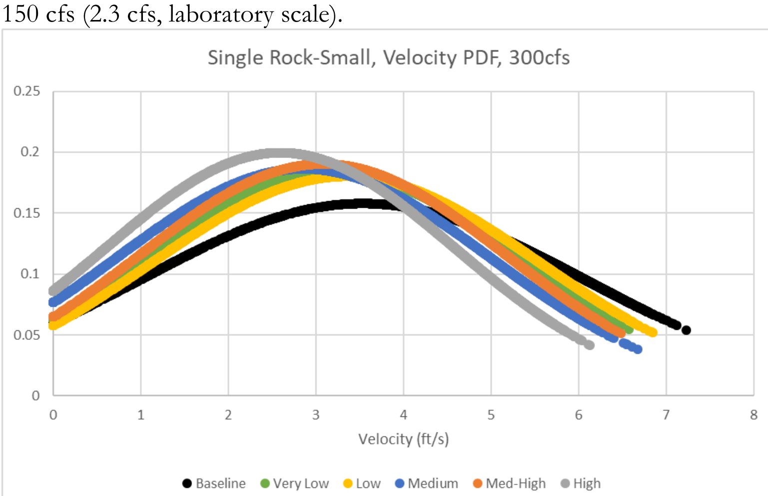

Figure D- 10 Small rock, single rock configuration velocity PDF curve at 300 cfs (4.7 cfs, laboratory scale).

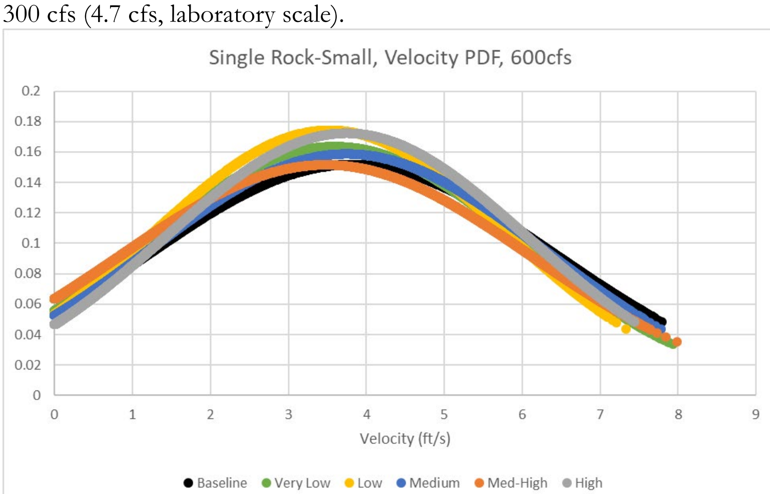

Figure D- 11 Small rock, single rock configuration velocity PDF curve at 600 cfs (9.4 cfs, laboratory scale).

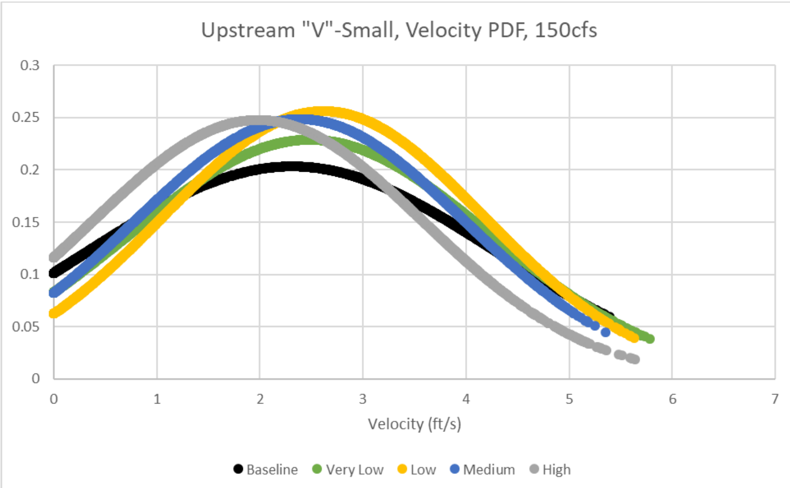

Figure D- 12 Small rock, Upstream V configuration velocity PDF curve at 150 cfs (2.3 cfs, laboratory scale).

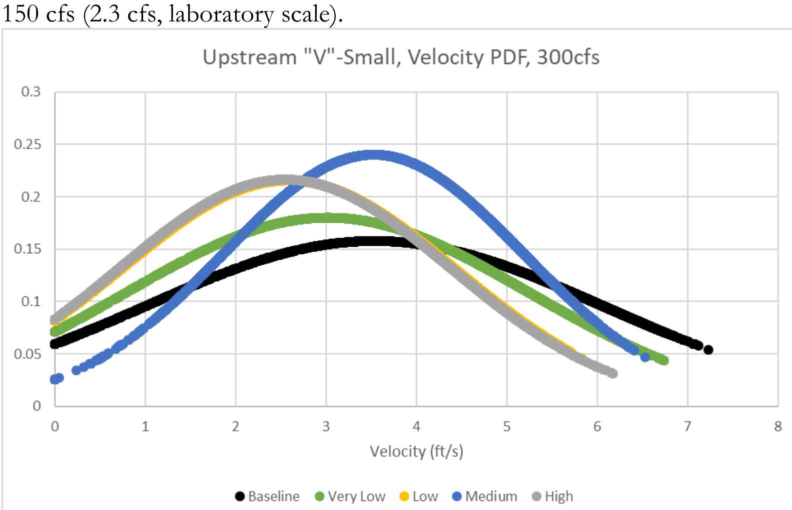

Figure D- 13 Small rock, Upstream V configuration velocity PDF curve at 300 cfs (4.7 cfs, laboratory scale).

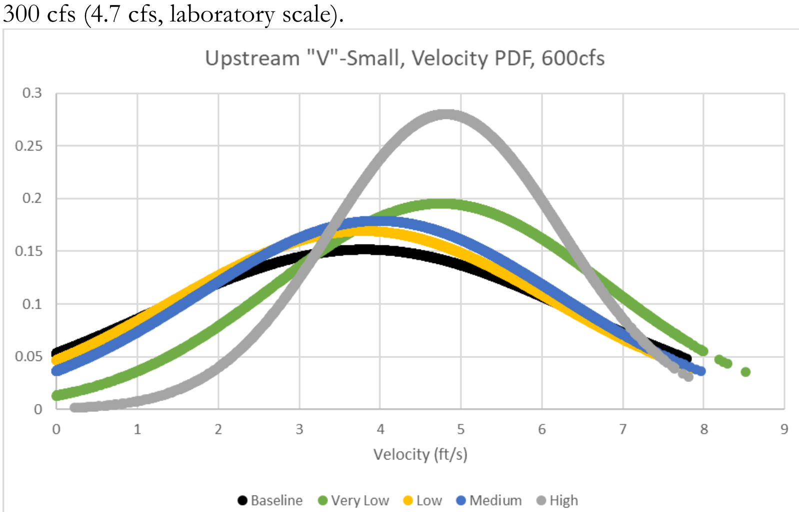

Figure D- 14 Small rock, Upstream V configuration velocity PDF curve at 600 cfs (9.4 cfs, laboratory scale).

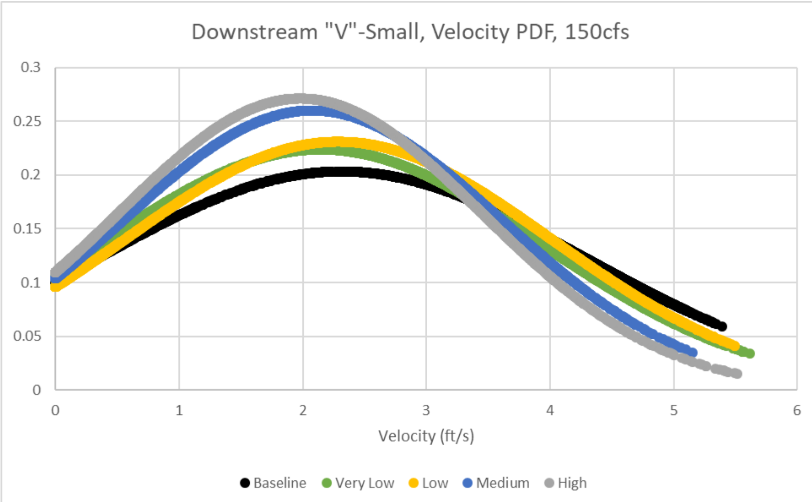

Figure D- 15 Small rock, Downstream V configuration velocity PDF curve at 150 cfs (2.3 cfs, laboratory scale).

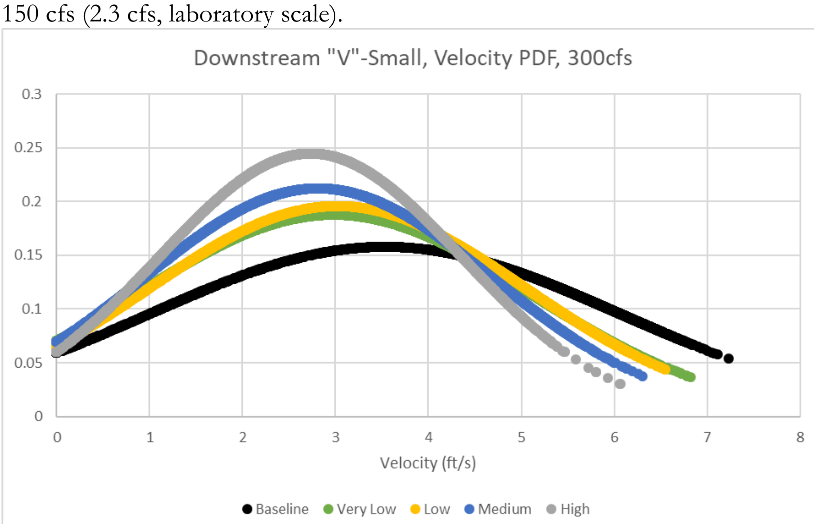

Figure D- 16 Small rock, Downstream V configuration velocity PDF curve at 300 cfs (4.7 cfs, laboratory scale).

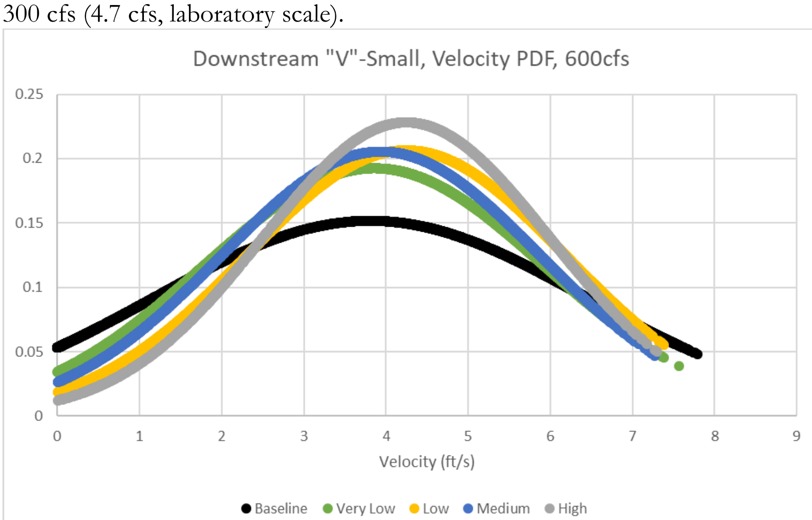

Figure D- 17 Small rock, Downstream V configuration velocity PDF curve at 600 cfs (9.4 cfs, laboratory scale).

Appendix E: Velocity Ratio of Boulder Clusters to Baseline

Large Rock

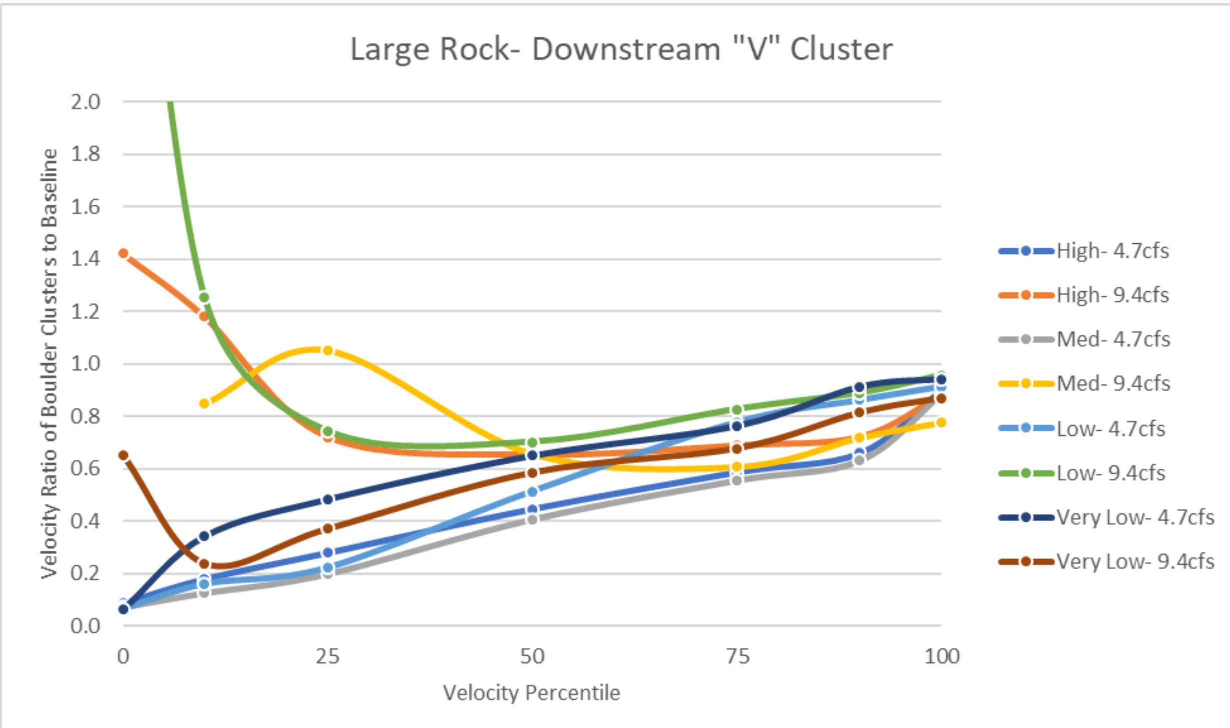

Figure E- 1 The ratio of cluster velocity to baseline over the velocity percentiles for large rock, Downstream V configuration at all densities and tested flow rates.

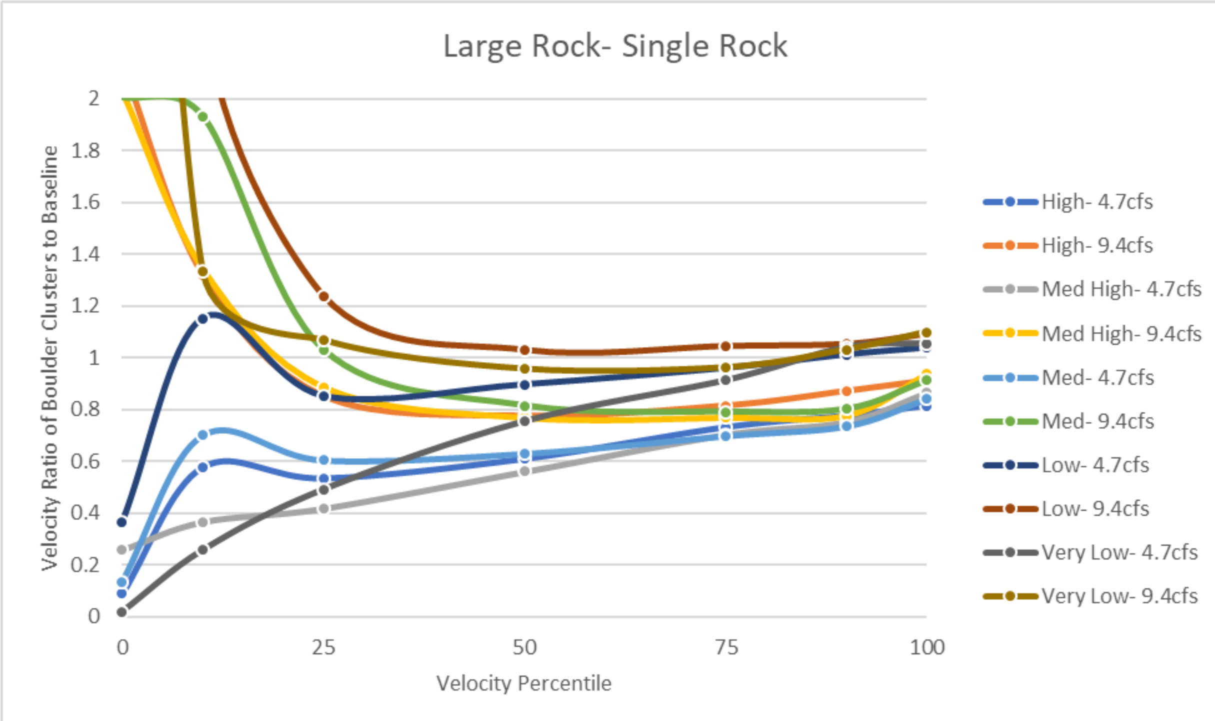

Figure E- 2 The ratio of cluster velocity to baseline over the velocity percentiles for large rock, single configuration at all densities and tested flow rates.

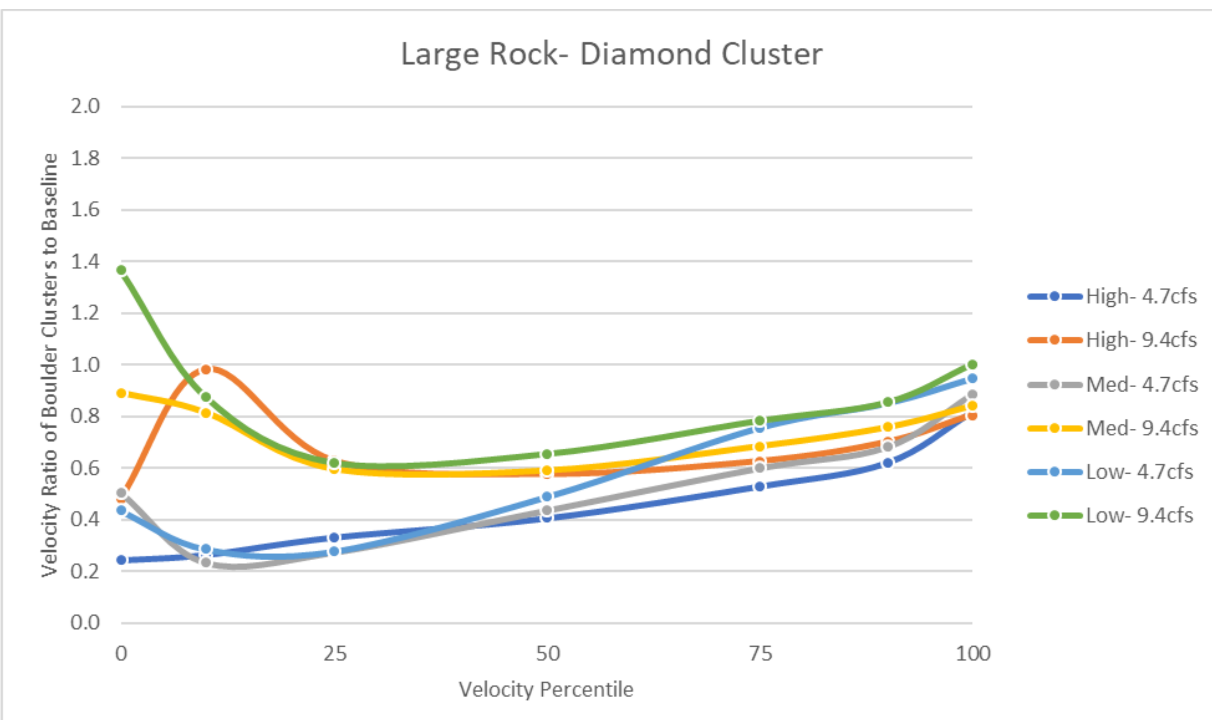

Figure E- 3 The ratio of cluster velocity to baseline over the velocity percentiles for large rock, Diamond configuration at all densities and tested flow rates.

Small Rock

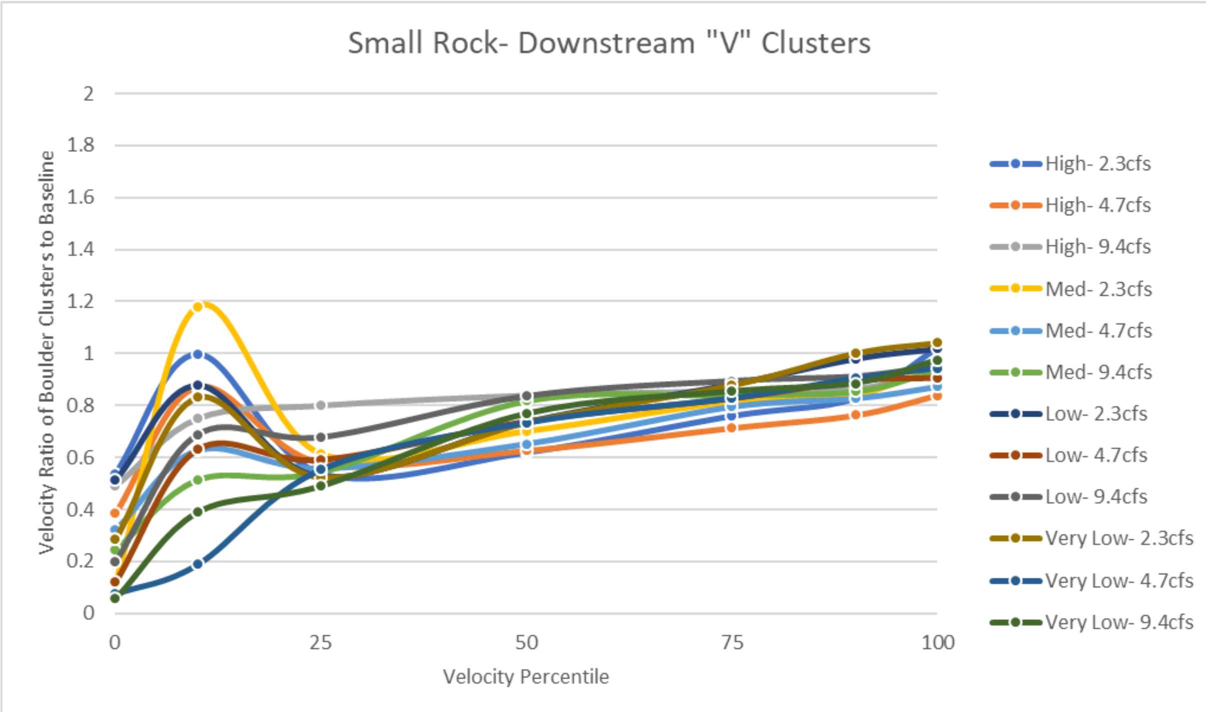

Figure E- 4 The ratio of cluster velocity to baseline over the velocity percentiles for small rock, Downstream V configuration at all densities and tested flow rates.

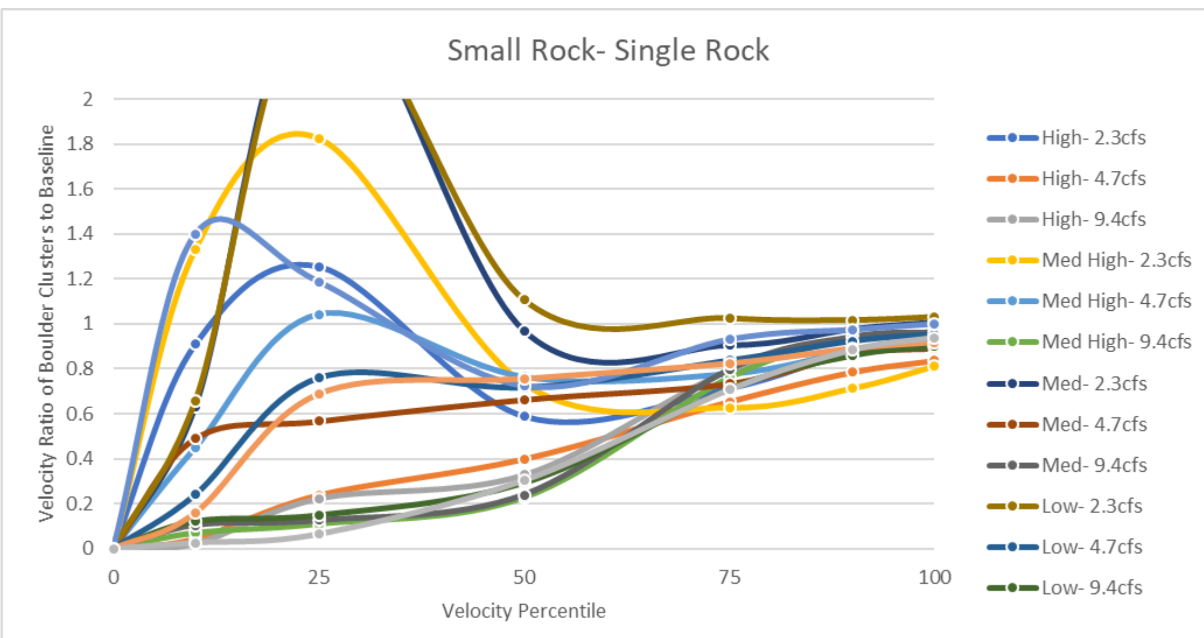

Figure E- 5 The ratio of cluster velocity to baseline over the velocity percentiles for small rock, single rock configuration at all densities and tested flow rates.

Appendix F: Velocity Vectors and Magnitude

The large rock dataset was originally generated for Report ST-2019-1726-01 for representation of flow in the LA River and were not changed for this report. For ease of comparison, the small rock dataset is also presented in prototype units as it would relate to the LA River. To convert the results to model scale, divide the velocity by a factor of 2.

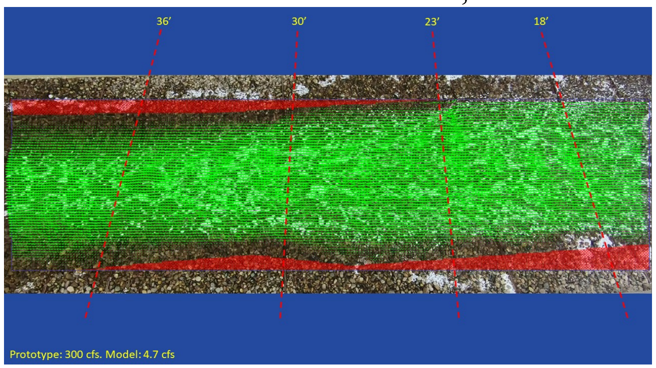

Figure F-1. PIVLab output of velocity vectors at 300 cfs baseline flow through the channel. Baseline ADV measurement transects are indicated with dotted lines. Distances marked in figure represent offset downstream from the model headbox. Red areas are "masked" portions that are either too shallow or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

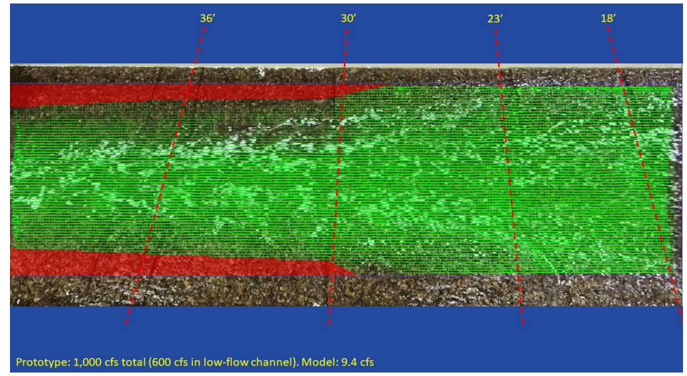

Figure F-3. PIVLab output of velocity vectors at 600 cfs baseline flow through the channel. Baseline ADV measurement transects are indicated with dotted lines. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

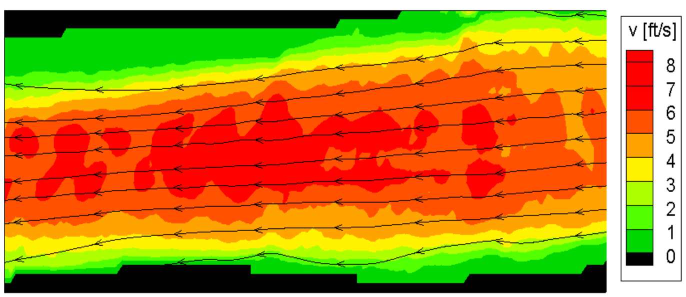

Figure F-2. TecPlot output for velocity at 300 cfs baseline flow through the channel. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

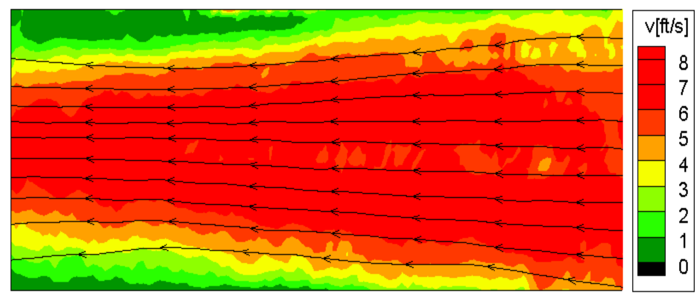

Figure F-4. TecPlot output for 600 cfs baseline flow through the channel. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

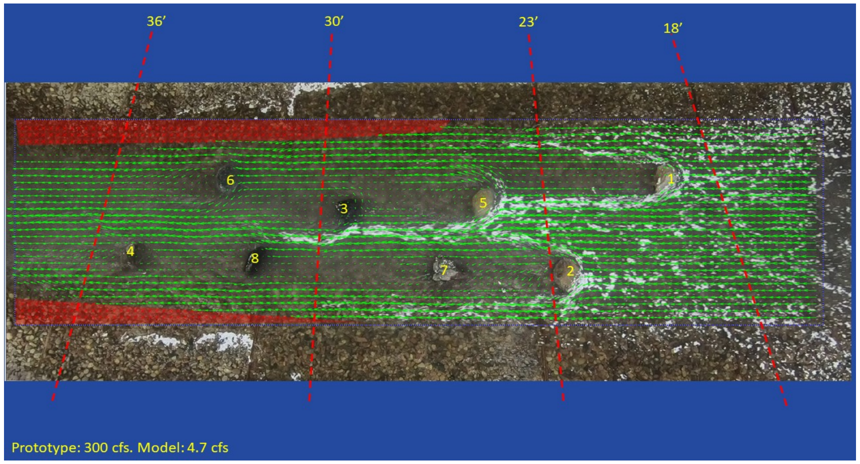

Figure F-5. PIVLab output of velocity vectors at 300 cfs for the single large rock, high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective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

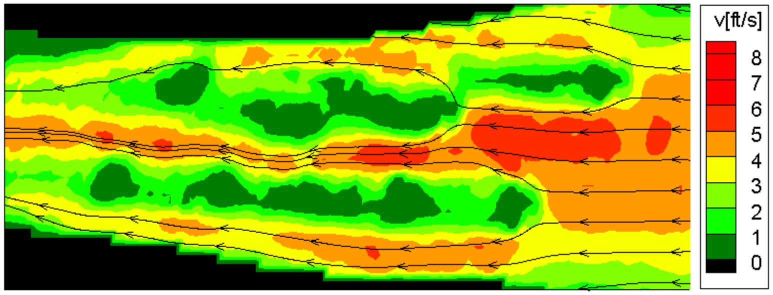

Figure F-6. TecPlot output for velocity at 300 cfs at the single large rock, high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

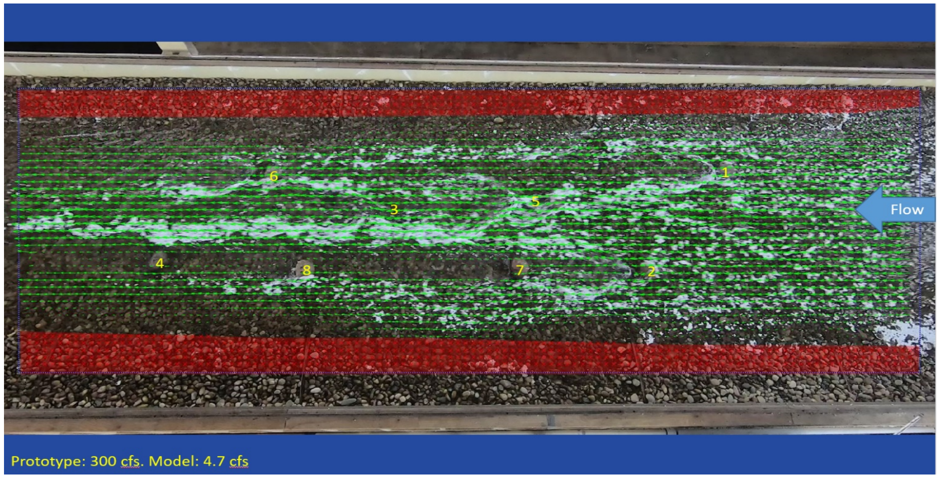

Figure F-7. PIVLab output of velocity vectors at 300 cfs at the single small rock, high density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

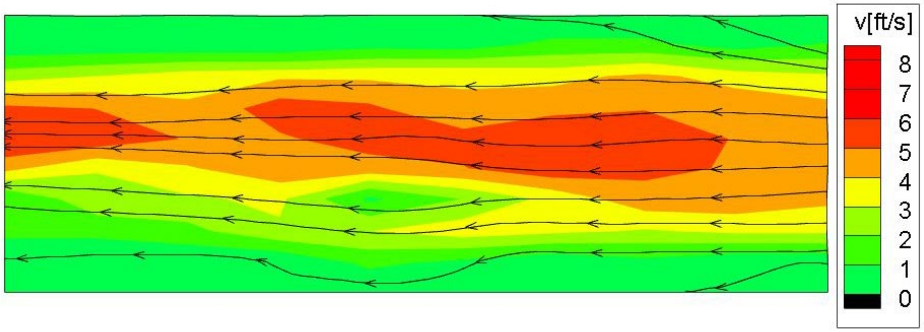

Figure F-8. TecPlot output for velocity at 300 cfs at the single small rock, high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

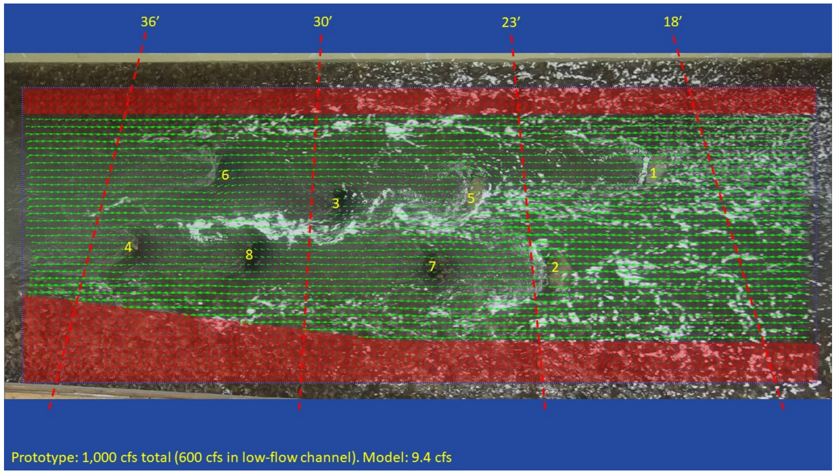

Figure F-9. PIVLab output of velocity vectors at 600 cfs at the single large rock, high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

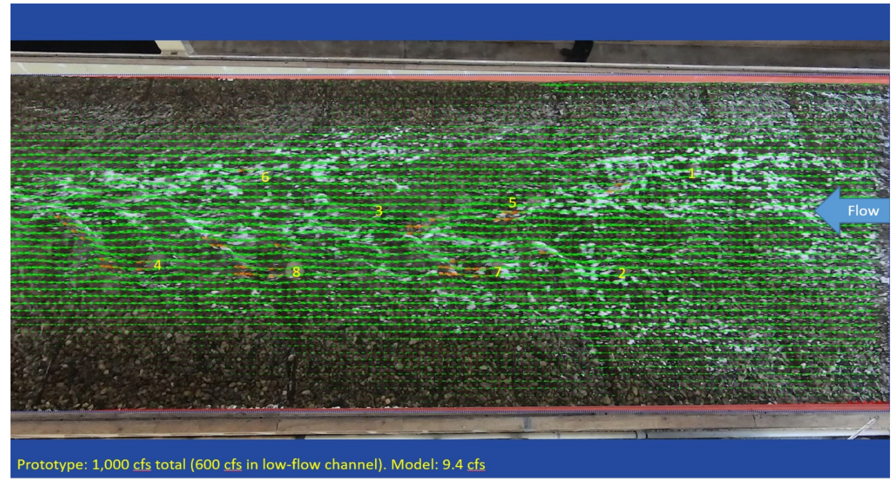

Figure F-11. PIVLab output of velocity vectors at 600 cfs at the single small rock, high density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

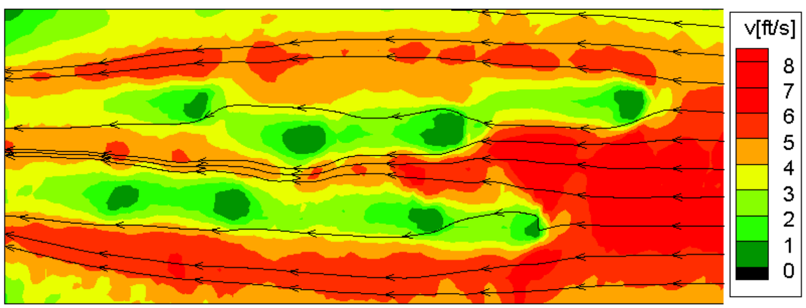

Figure F-10. TecPlot output for velocity at 600 cfs at the single large rock, high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

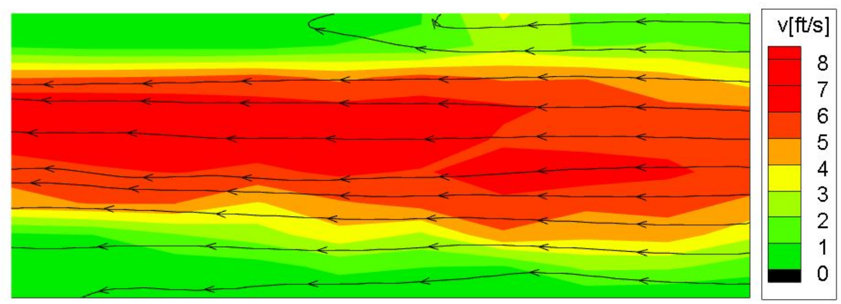

Figure F-12. TecPlot output for velocity at 600 cfs at the single small rock, high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

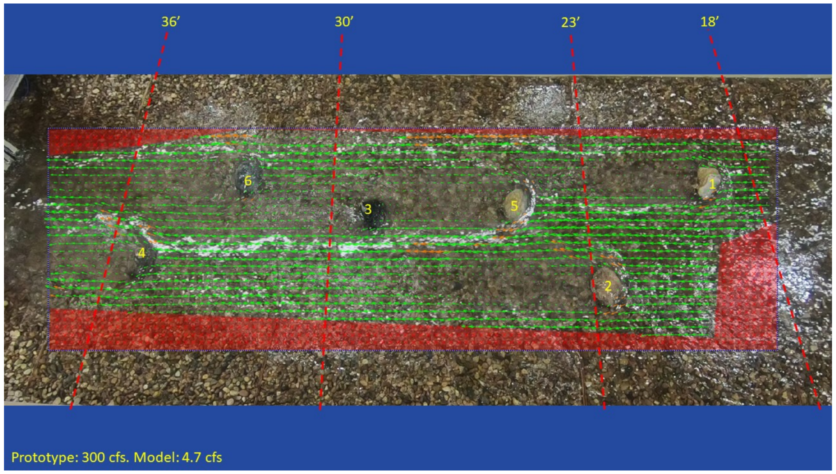

Figure F-13. PIVLab output of velocity vectors at 300 cfs at the single large rock, medium high-density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too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

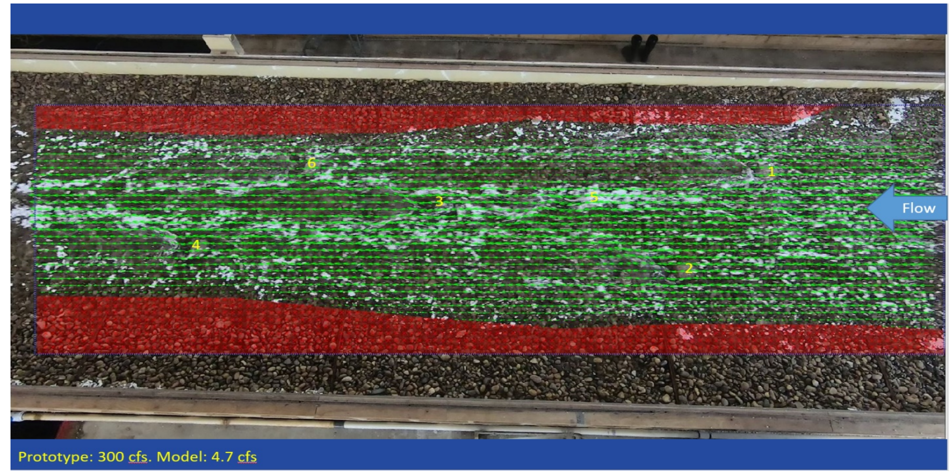

Figure F-15. PIVLab output of velocity vectors at 300 cfs at the single small rock, medium-high density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

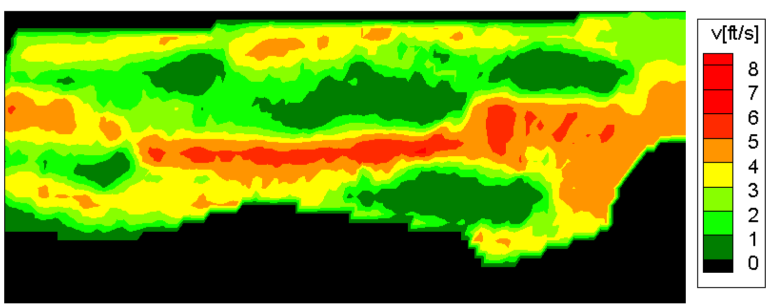

Figure F-14. TecPlot output for velocity at 300 cfs at the single large rock, medium-high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

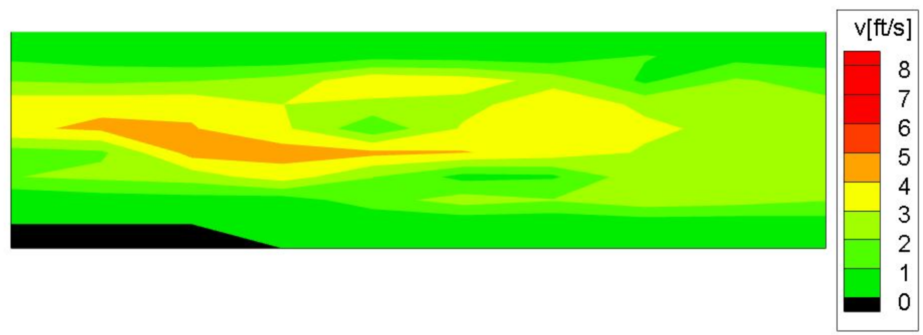

Figure F-16. TecPlot output for velocity at 300 cfs at the single small rock, medium-high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

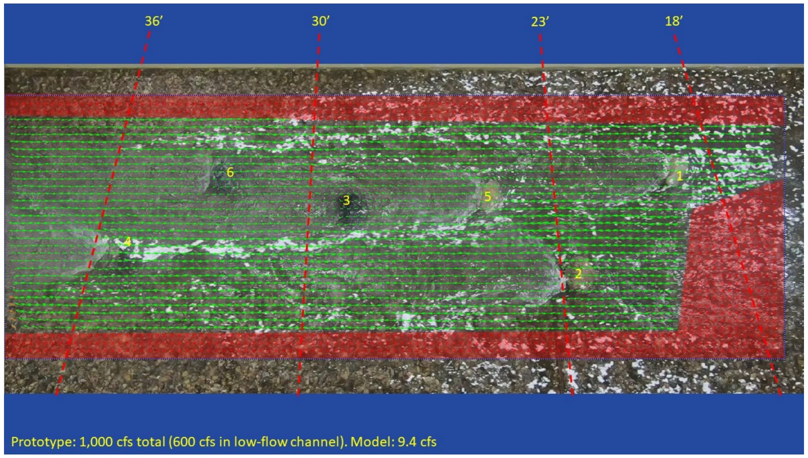

Figure F-17. PIVLab output of velocity vectors at 600 cfs at the single large rock, medium-high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

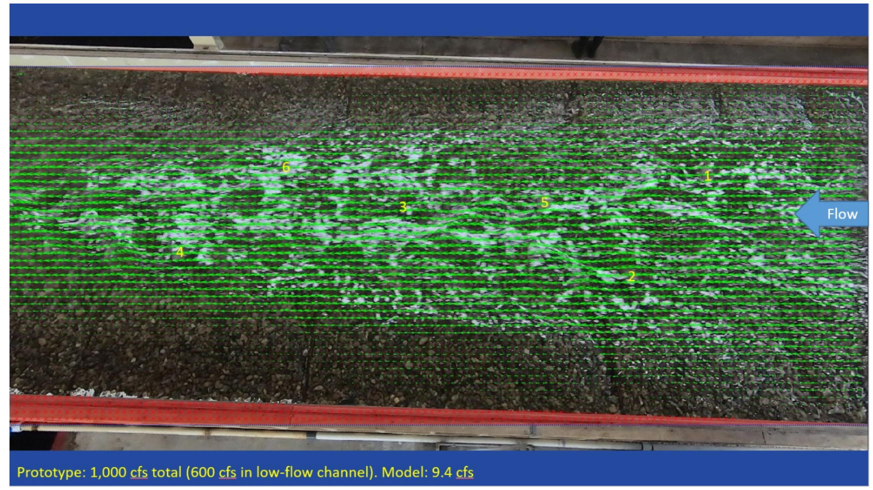

Figure F-19. PIVLab output of velocity vectors at 600 cfs at the single small rock, medium-high density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

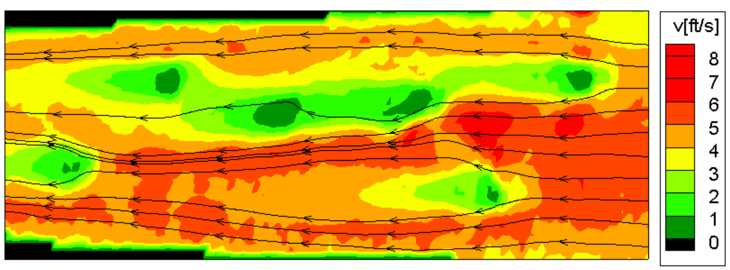

Figure F-18. TecPlot output for velocity at 600 cfs at the single large rock, medium-high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

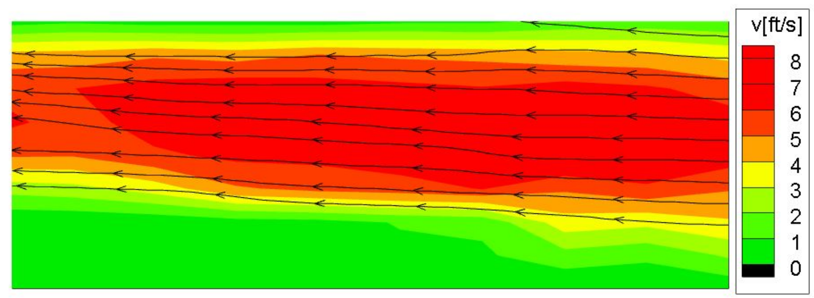

Figure F-20. TecPlot output for velocity at 600 cfs at the single small rock, medium-high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

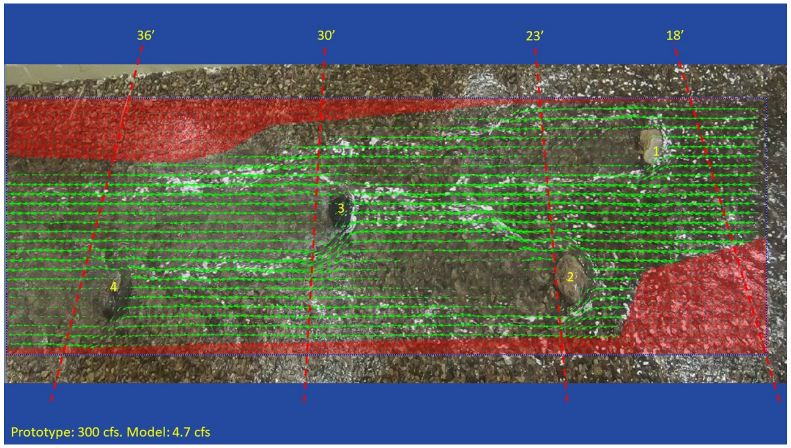

Figure F-21. PIVLab output of velocity vectors at 300 cfs at the single large rock, medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

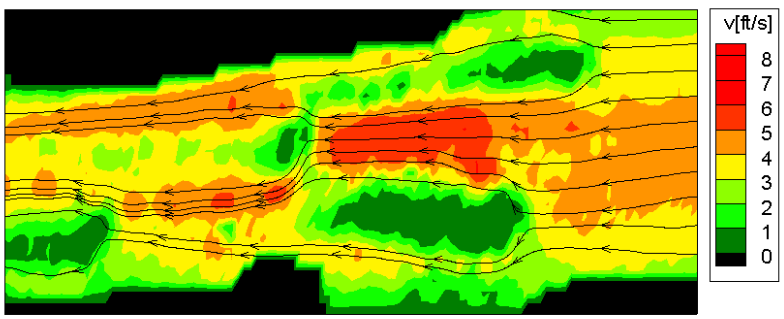

Figure F-22. TecPlot output for velocity at 300 cfs at the single large rock, medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

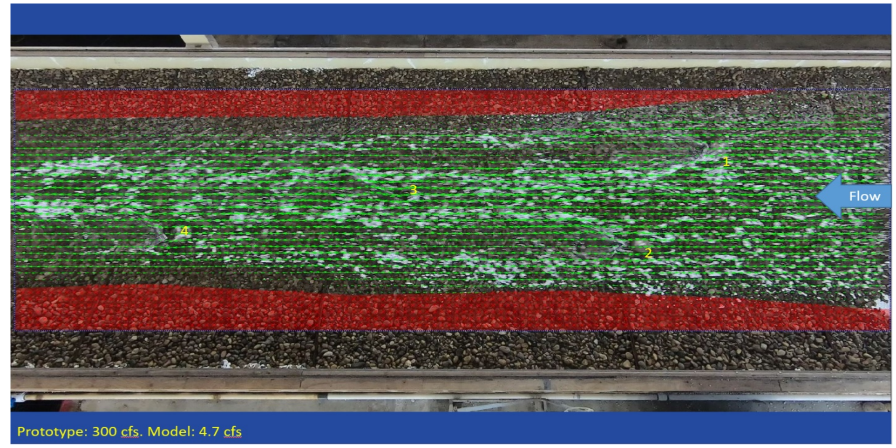

Figure F-23. PIVLab output of velocity vectors at 300 cfs at the single small rock, medium density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

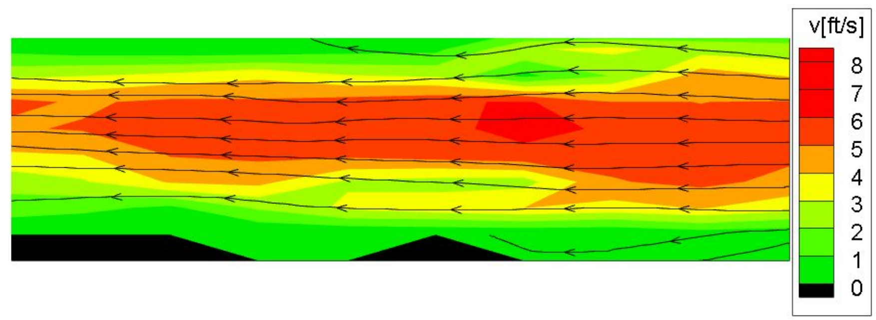

Figure F-24. TecPlot output for velocity at 300 cfs at the single small rock, medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

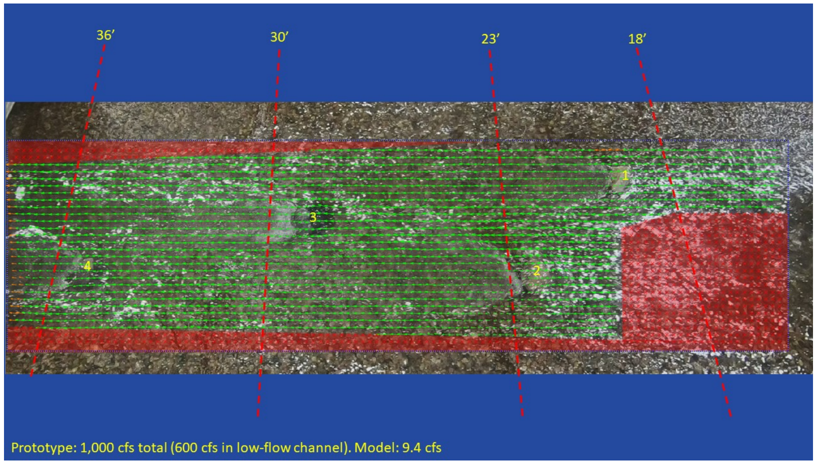

Figure F-25. PIVLab output of velocity vectors at 600 cfs at the single large rock, medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

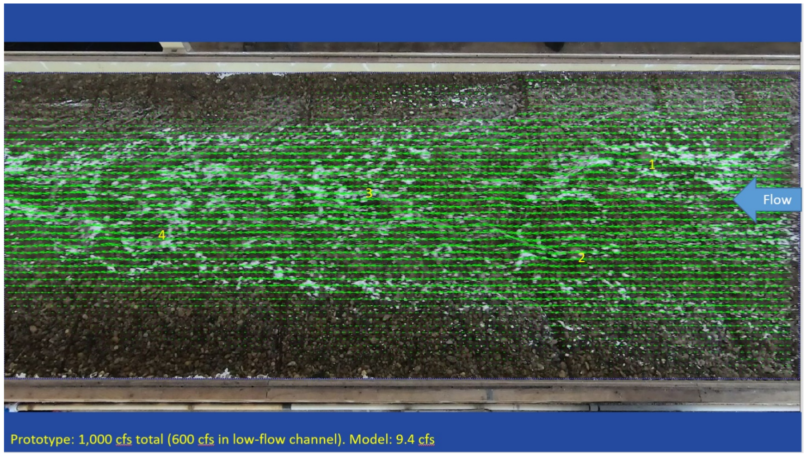

Figure F-26. PIVLab output of velocity vectors at 600 cfs at the single small rock, medium density configuration through the channel. Rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

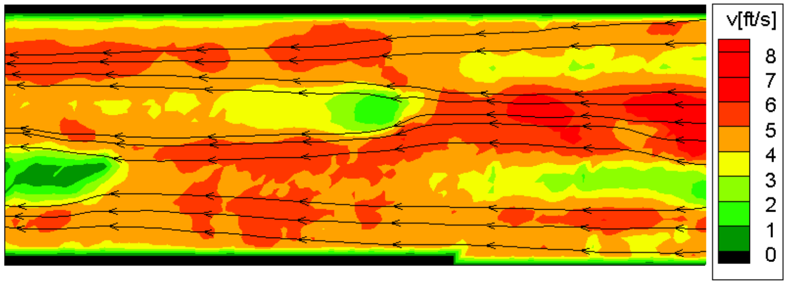

Figure F-25b TecPlot output for velocity at 600 cfs at the single large rock, medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for and were masked.

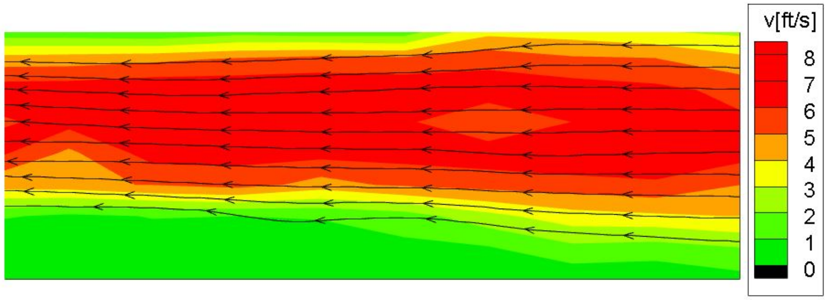

Figure F-27. TecPlot output for velocity at 600 cfs at the single small rock, medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

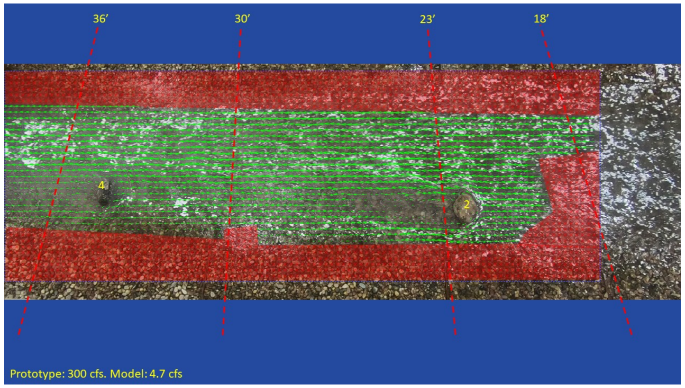

Figure F-28. PIVLab output of velocity vectors at 300 cfs at the single large rock, low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

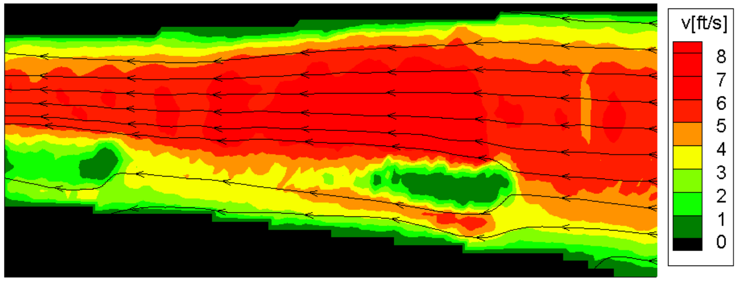

Figure F-29. TecPlot output for velocity at 300 cfs at the single large rock, low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

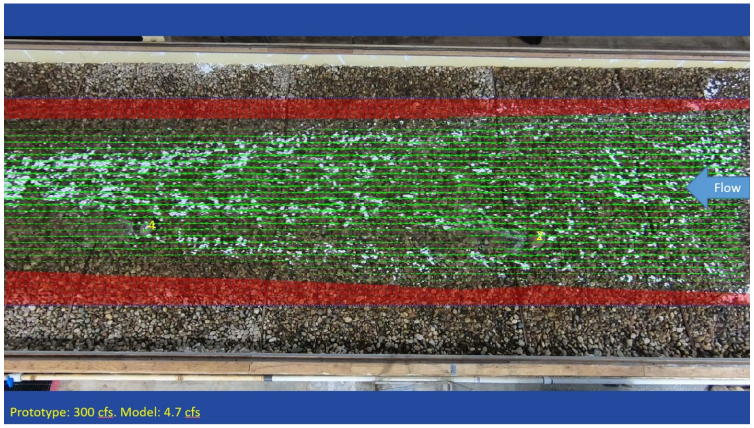

Figure F-30. PIVLab output of velocity vectors at 300 cfs at the single small rock, low density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

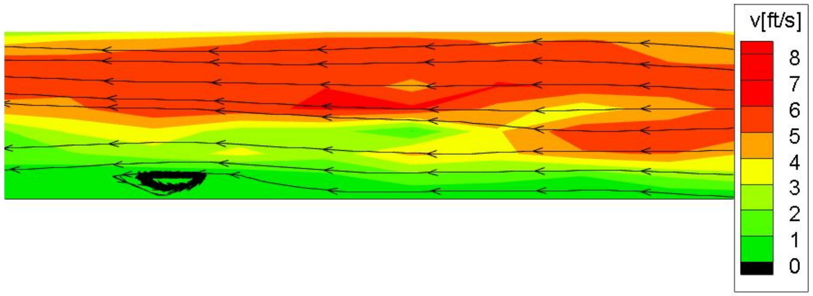

Figure F-31. TecPlot output for velocity at 300 cfs at the single small rock, low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

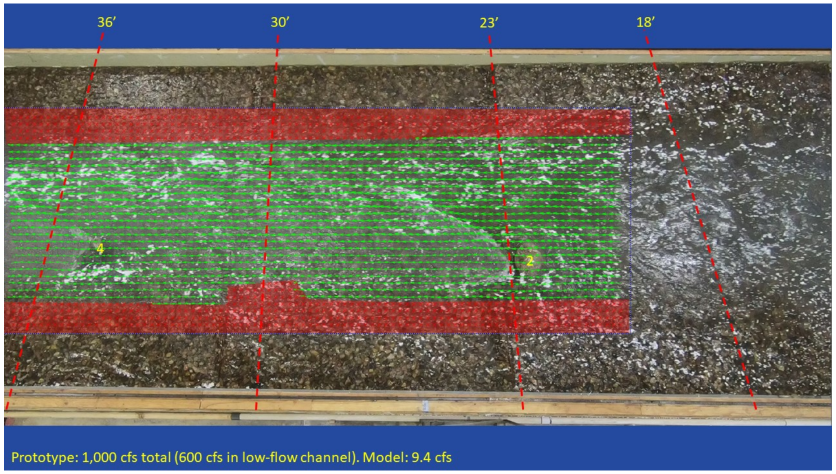

Figure F-32. PIVLab output of velocity vectors at 600 cfs at the single large rock, low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

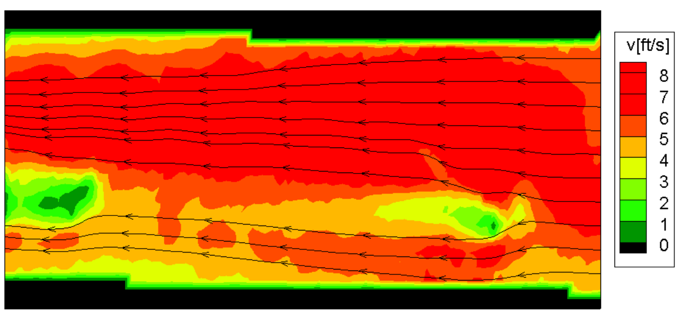

Figure F-33. TecPlot output for velocity at 600 cfs at the single large rock, low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

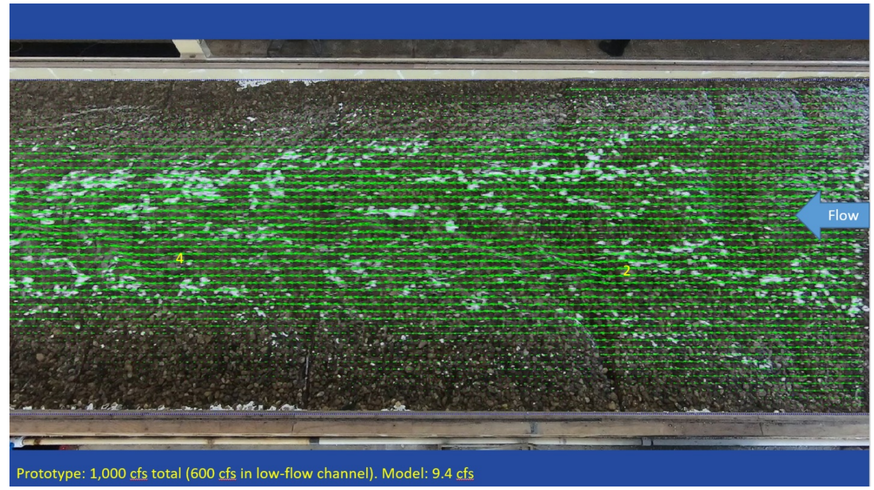

Figure F-34. PIVLab output of velocity vectors at 600 cfs at the single small rock, low density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

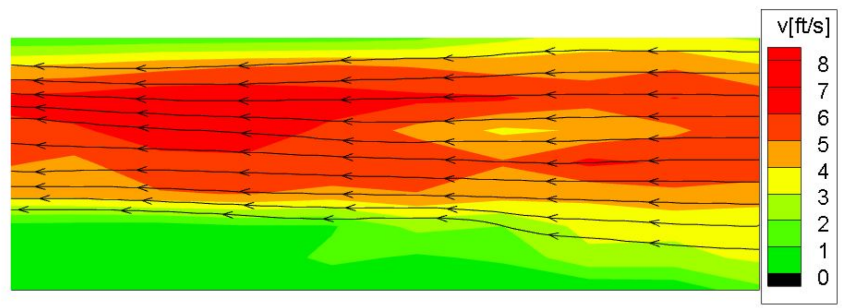

Figure F-35. TecPlot output for velocity at 600 cfs at the single small rock, low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

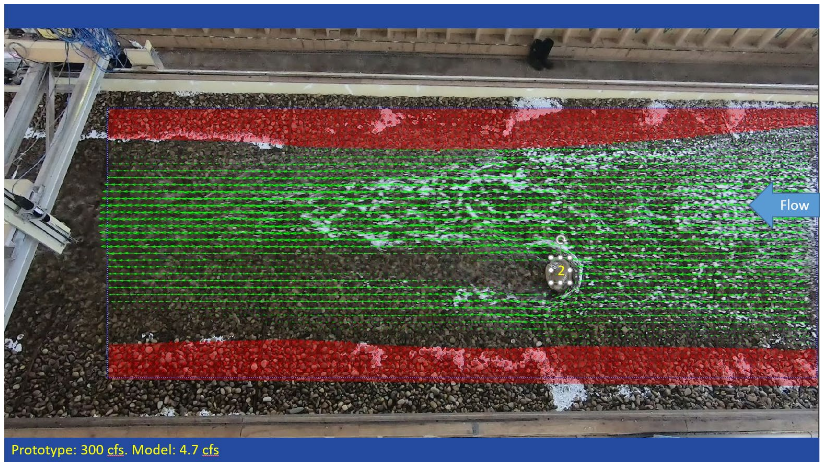

Figure F- 36 PIVLab output of velocity vectors at 300 cfs at the single large rock, very low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are “masked” portions

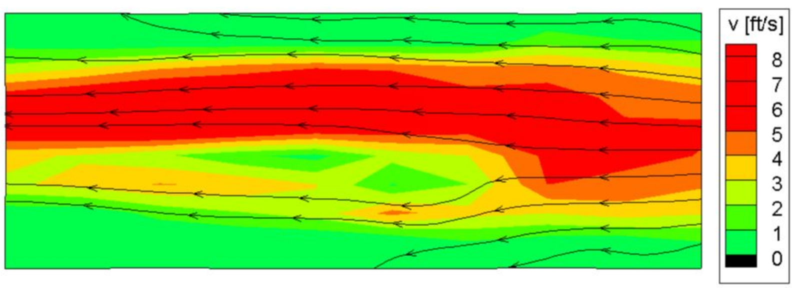

Figure F- 37 TecPlot output for velocity at 300 cfs at the single small rock, very low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

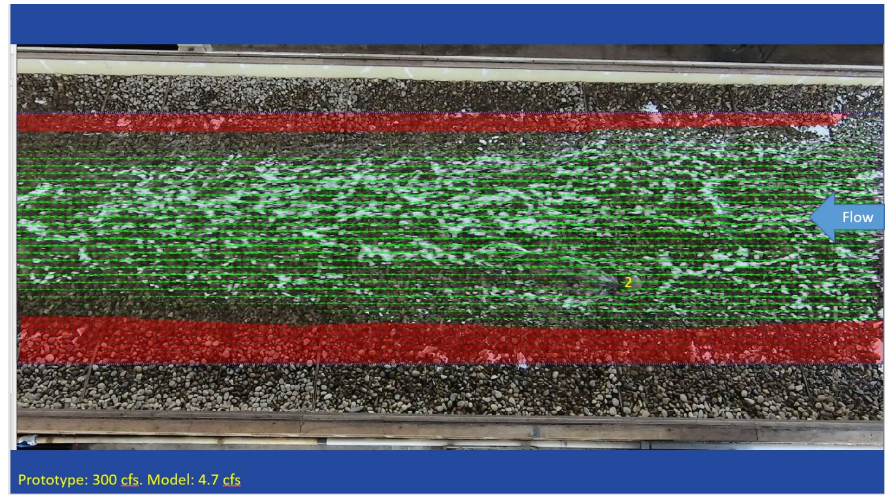

Figure F-36. PIVLab output of velocity vectors at 300 cfs at the single small rock, very low density configuration through the channel. Rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

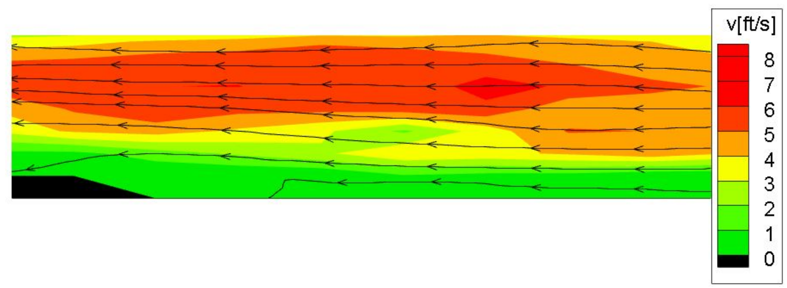

Figure F-37. TecPlot output for velocity at 300 cfs at the single small rock, very low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

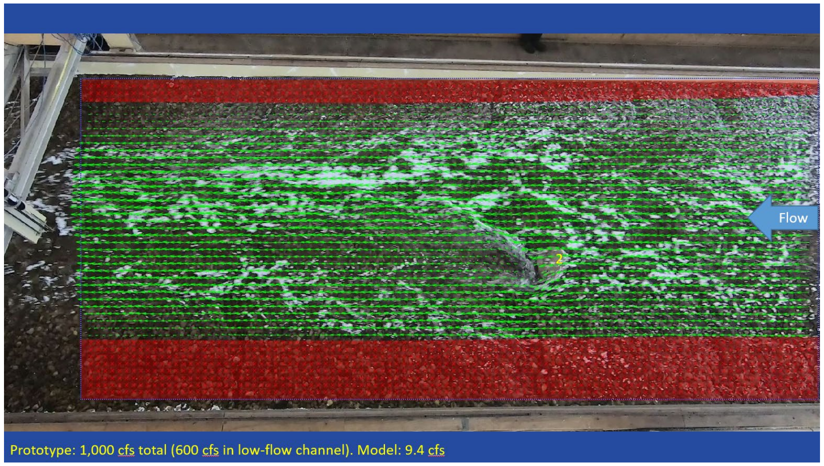

Figure F- 38 PIVLab output of velocity vectors at 600 cfs at the single large rock, very low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are “masked” portions

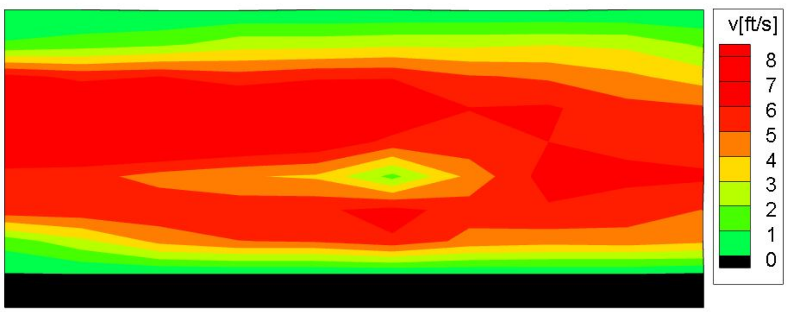

Figure F- 39 TecPlot output for velocity at 600 cfs at the single small rock, very low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

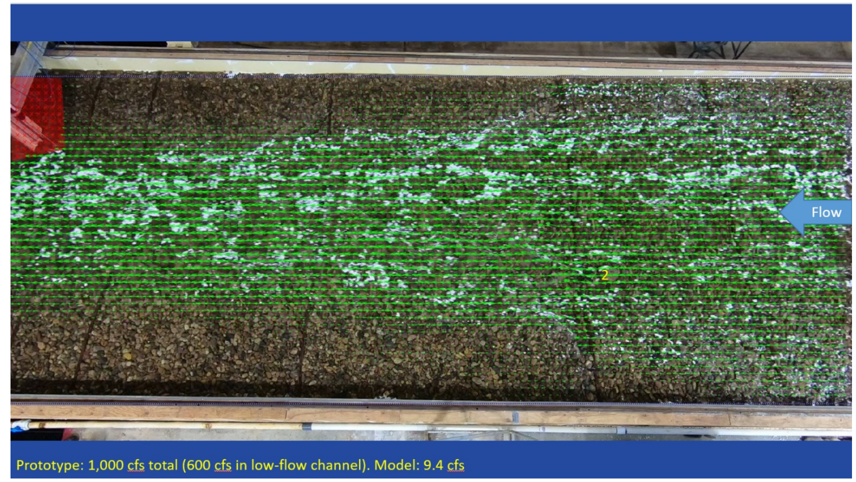

Figure F-38. PIVLab output of velocity vectors at 600 cfs at the single small rock, very low density configuration through the channel. Rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

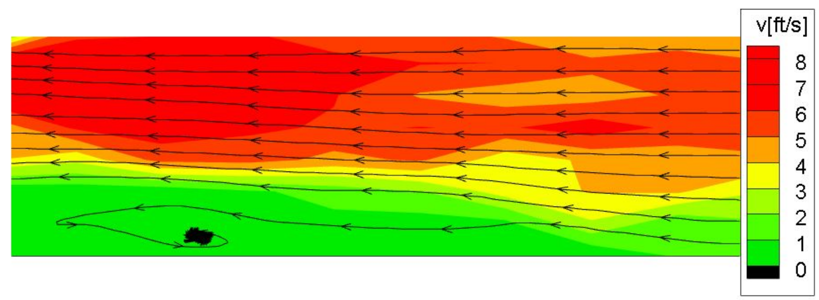

Figure F-39. TecPlot output for velocity at 600 cfs at the single small rock, very low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

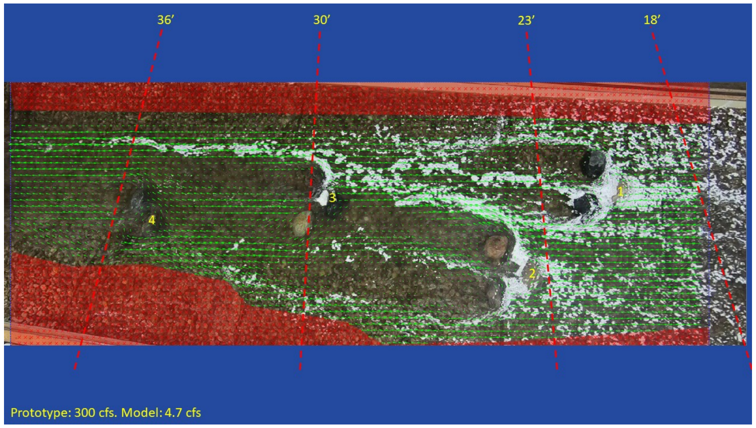

Figure F-40. PIVLab output of velocity vectors at 300 cfs at the large rock upstream "V", high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

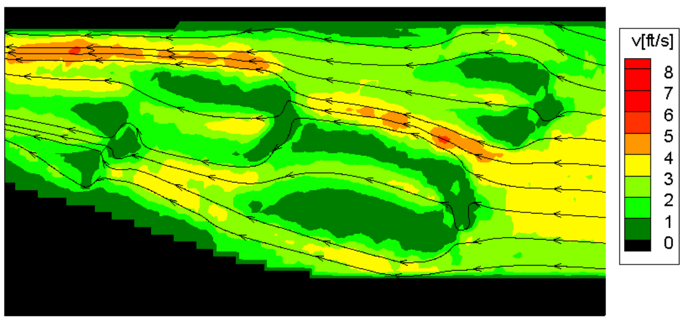

Figure F-41. TecPlot output for velocity at 300 cfs at the large rock upstream "V", high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

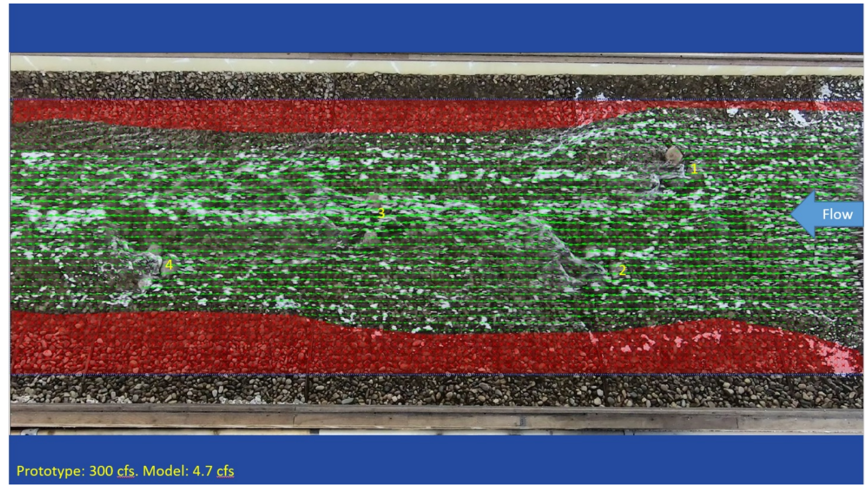

Figure F-42. PIVLab output of velocity vectors at 300 cfs at the small rock upstream "V", high density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

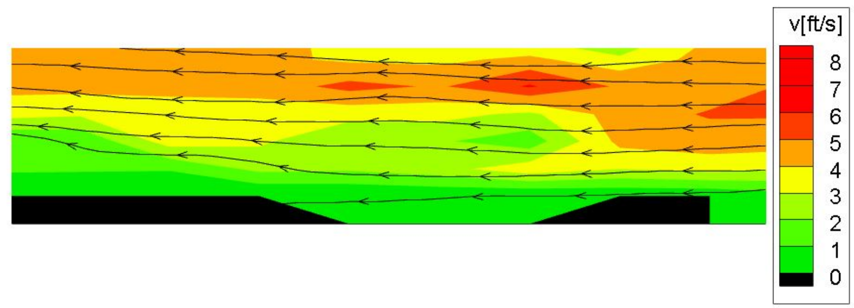

Figure F-43. TecPlot output for velocity at 300 cfs at the small rock upstream "V", high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

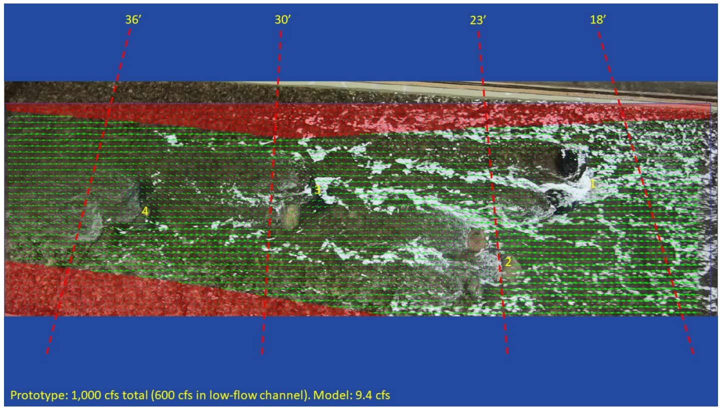

Figure F-44. PIVLab output of velocity vectors at 600 cfs at the large rock upstream "V", high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

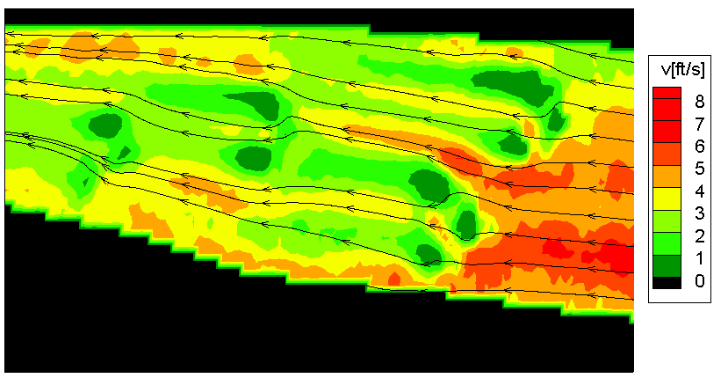

Figure F-45. TecPlot output for velocity at 600 cfs at the large rock upstream "V", high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

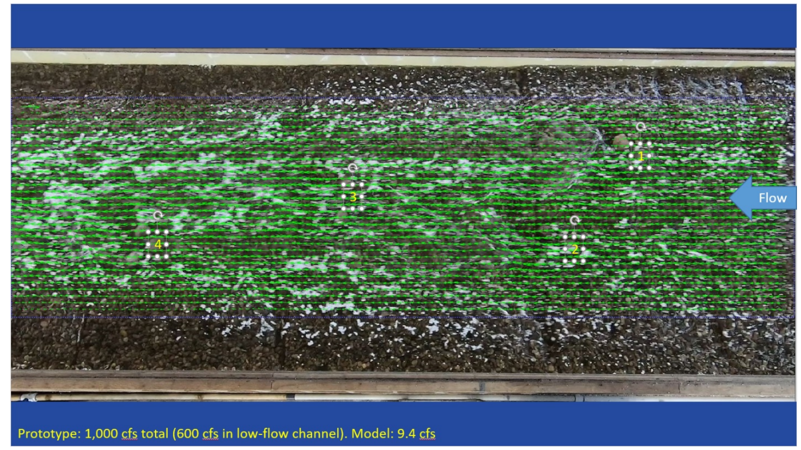

Figure F-46. PIVLab output of velocity vectors at 600 cfs at the small rock upstream "V", high density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

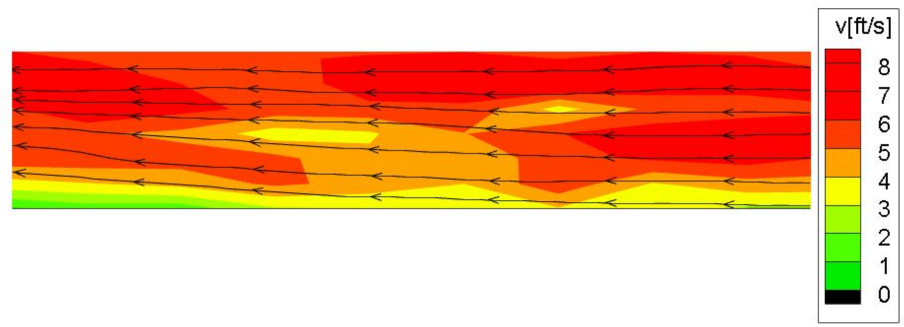

Figure F-47. TecPlot output for velocity at 600 cfs at the small rock upstream "V", high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

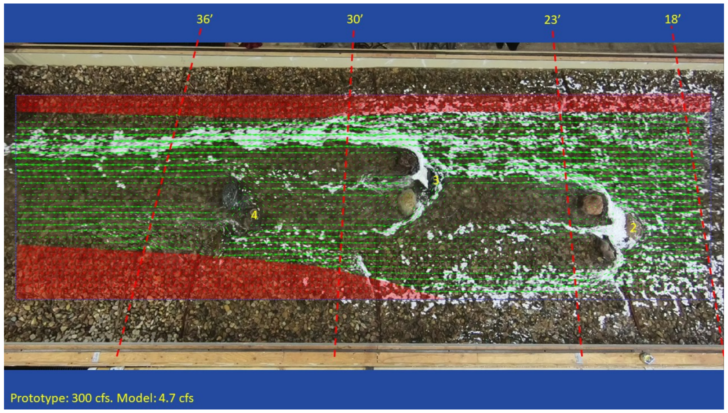

Figure F-48. PIVLab output of velocity vectors at 300 cfs at the large rock upstream "V", medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

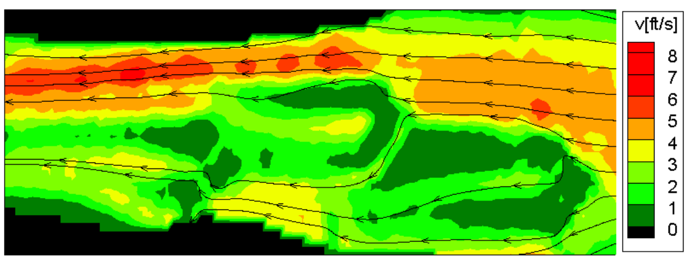

Figure F-49. TecPlot output for velocity at 300 cfs at the large rock upstream "V", medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

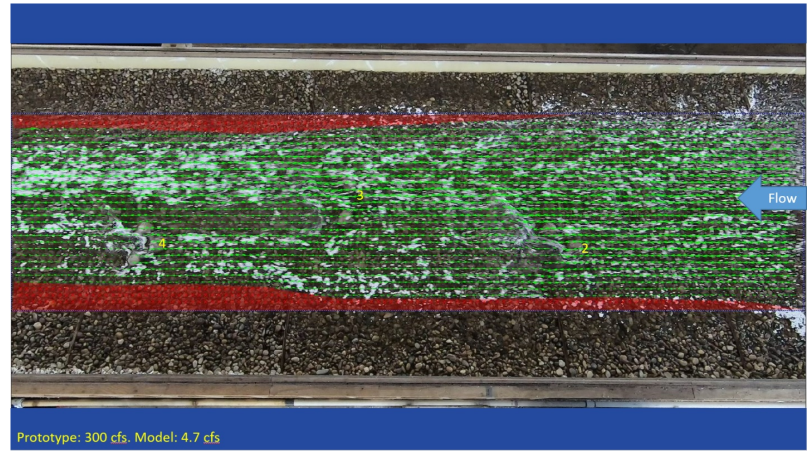

Figure F-50. PIVLab output of velocity vectors at 300 cfs at the small rock upstream "V", medium density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

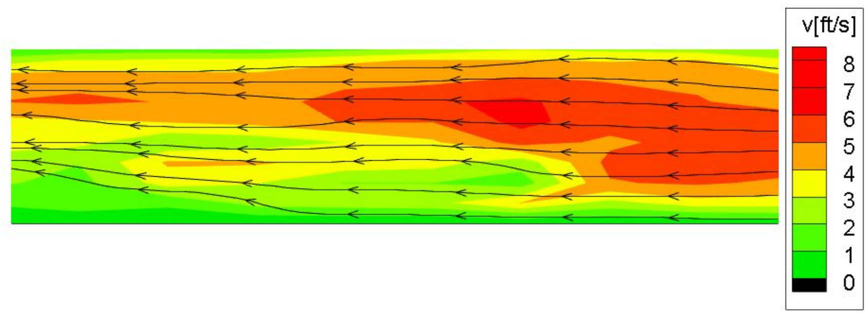

Figure F-51. TecPlot output for velocity at 300 cfs at the small rock upstream "V", medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

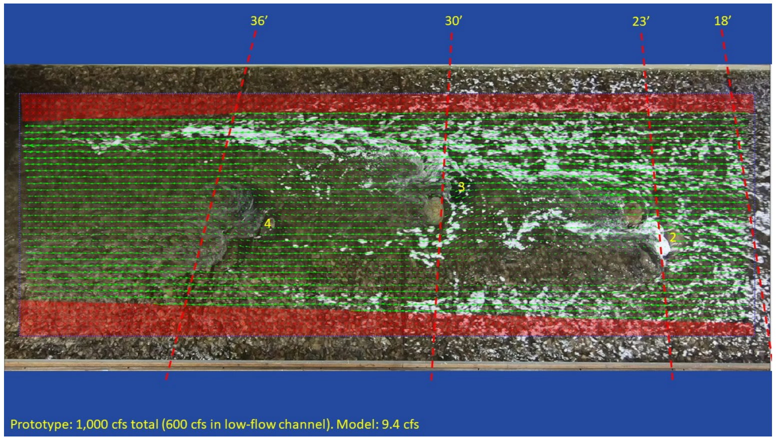

Figure F-52. PIVLab output of velocity vectors at 600 cfs at the large rock upstream "V", medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

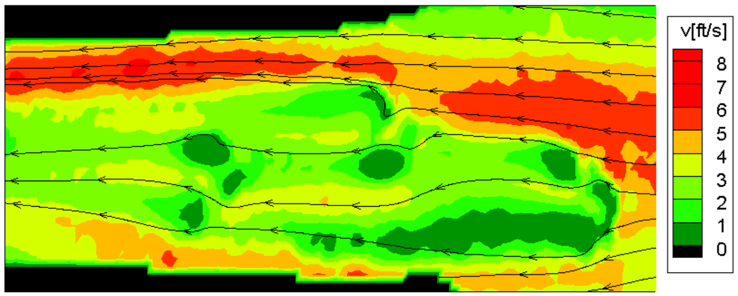

Figure F-53. TecPlot output for velocity at 600 cfs at the large rock upstream "V", medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

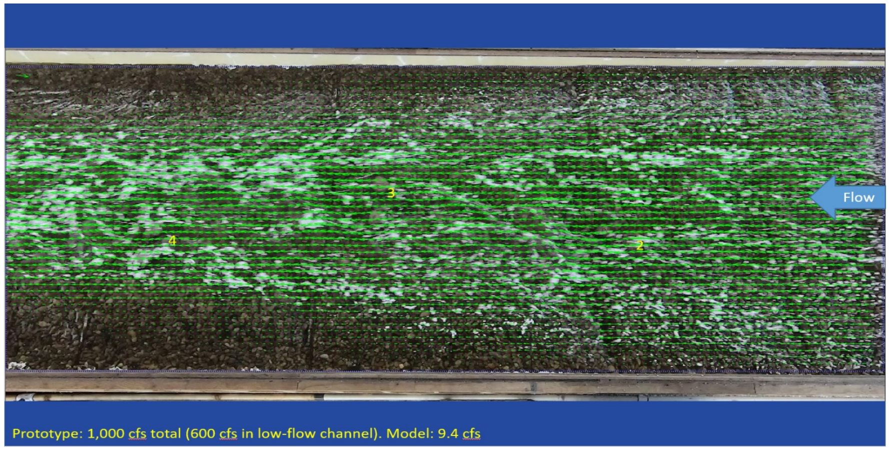

Figure F-54. PIVLab output of velocity vectors at 600 cfs at the small rock upstream "V", medium density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

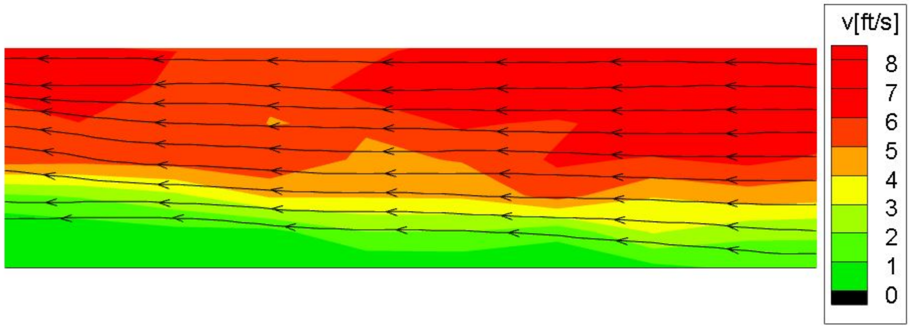

Figure F-55. TecPlot output for velocity at 600 cfs at the small rock upstream "V", medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

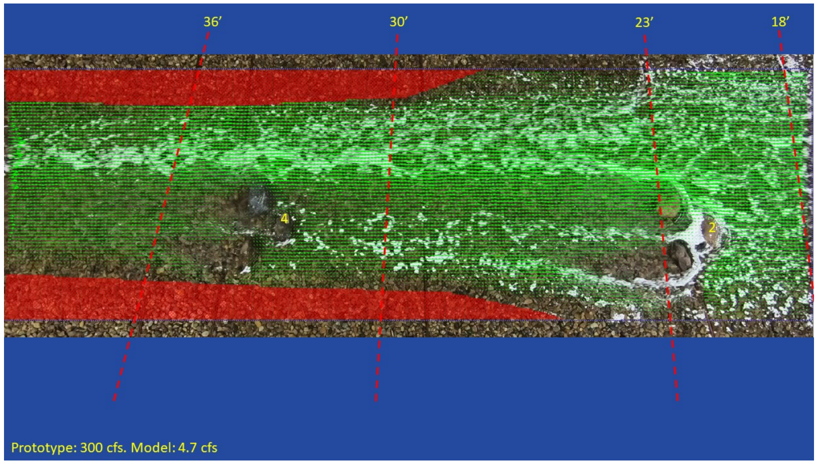

Figure F-56. PIVLab output of velocity vectors at 300 cfs at the large rock upstream "V", low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

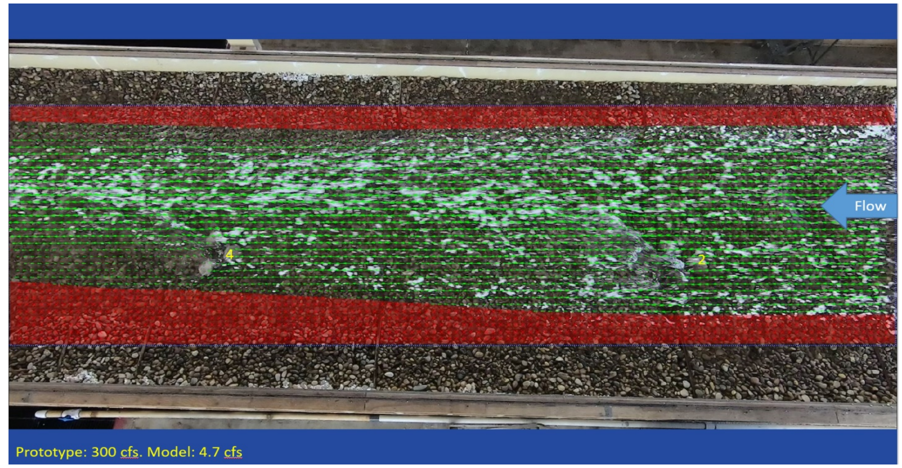

Figure F-58. PIVLab output of velocity vectors at 300 cfs at the small rock upstream "V", low density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

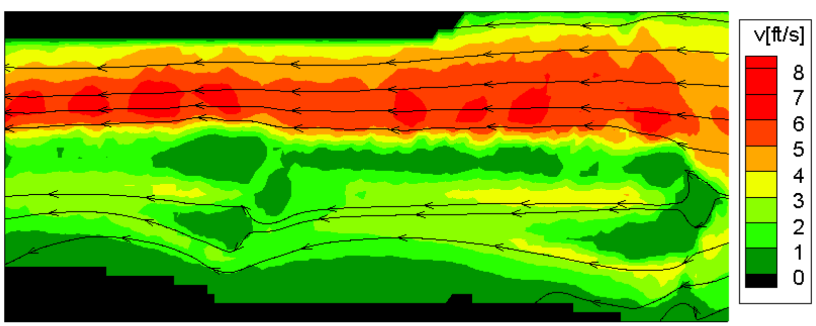

Figure F-57. TecPlot output for velocity at 300 cfs at the large rock upstream "V", low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

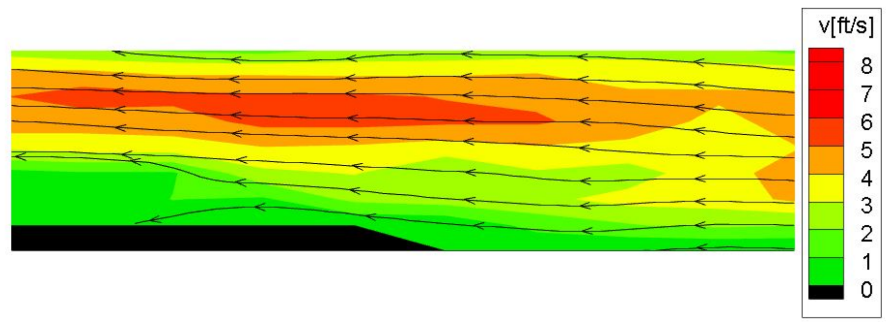

Figure F-59. TecPlot output for velocity at 300 cfs at the small rock upstream "V", low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

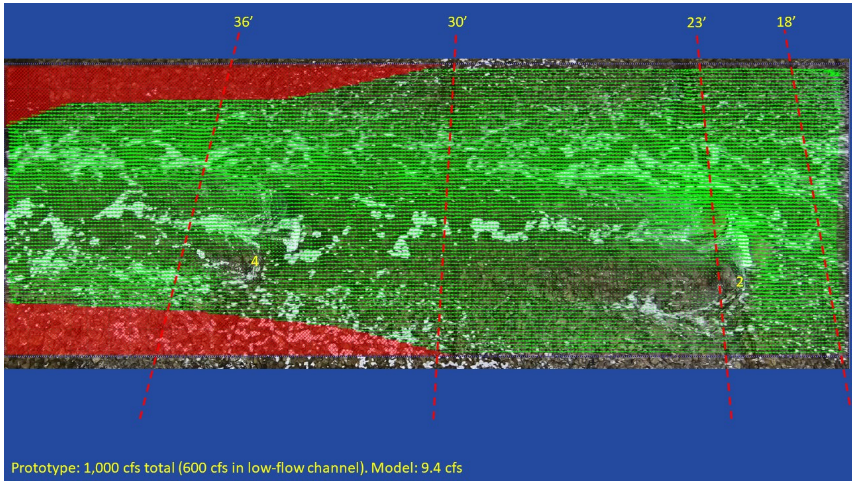

Figure F-60. PIVLab output of velocity vectors at 600 cfs at the large rock upstream “V”, low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

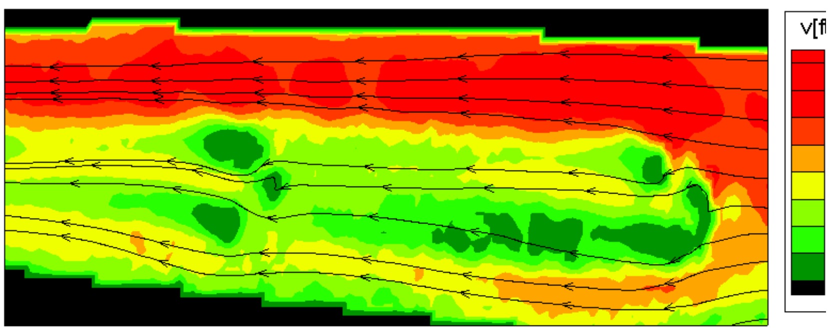

Figure F-61. TecPlot output for velocity at 600 cfs at the large rock upstream “V”, low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

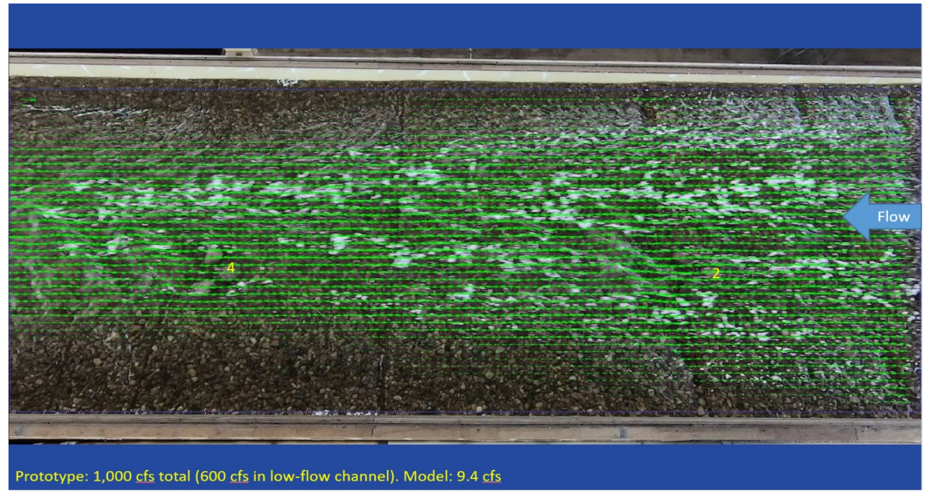

Figure F-62. PIVLab output of velocity vectors at 600 cfs at the small rock upstream “V”, low density configuration through the channel. Rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

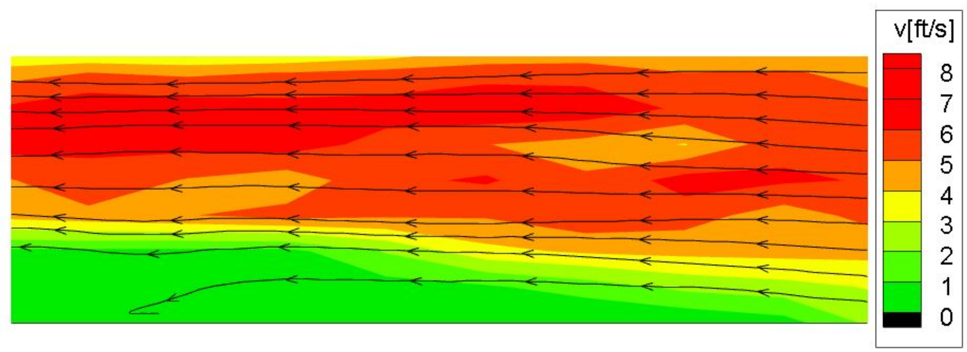

Figure F-63. TecPlot output for velocity at 600 cfs at the small rock upstream “V”, low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

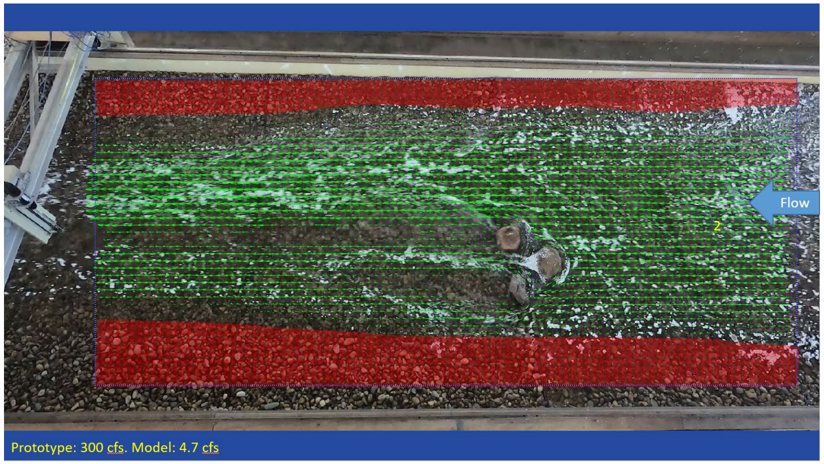

Figure F- 64 PIVLab output of velocity vectors at 300 cfs at the large rock upstream "V", very low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

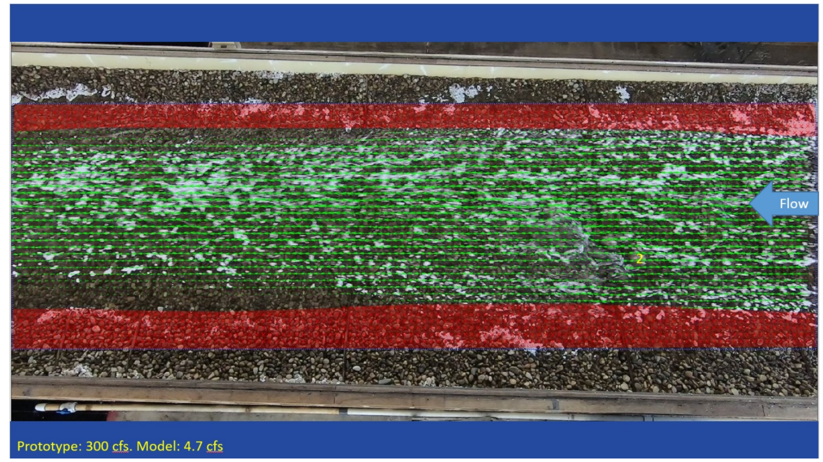

Figure F-64. PIVLab output of velocity vectors at 300 cfs at the small rock upstream "V", very low density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

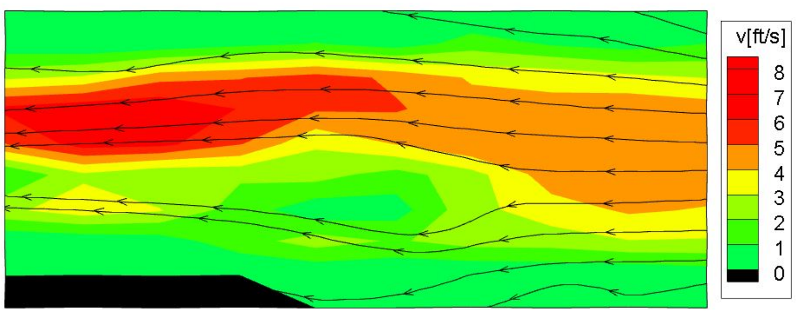

Figure F- 65 TecPlot output for velocity at 300 cfs at the large rock upstream "V", low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

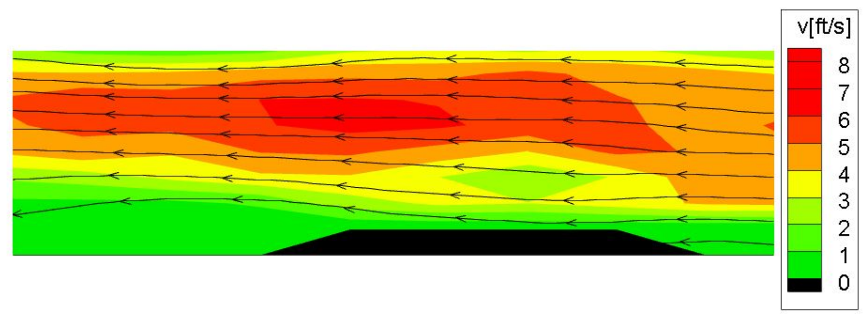

Figure F-65. TecPlot output for velocity at 300 cfs at the small rock upstream "V", very low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

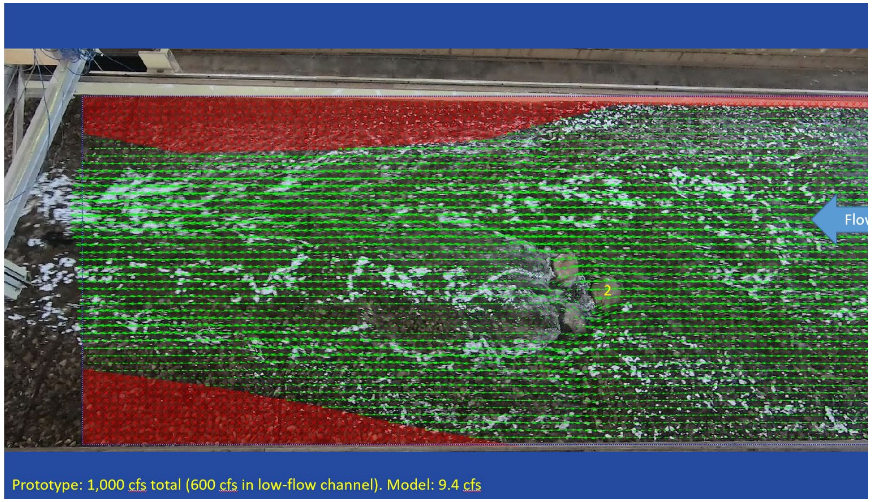

Figure F- 66 PIVLab output of velocity vectors at 600 cfs at the large rock upstream "V", very low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

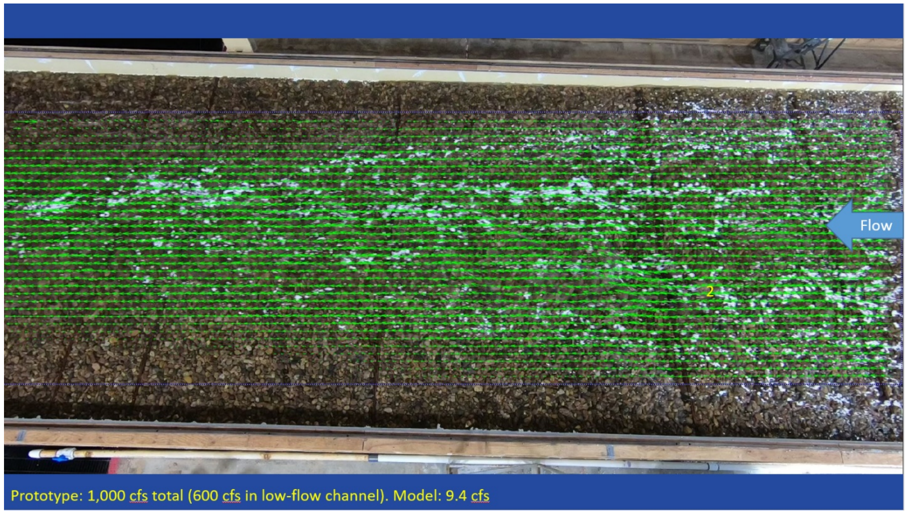

Figure F-66. PIVLab output of velocity vectors at 600 cfs at the small rock upstream "V", very low density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

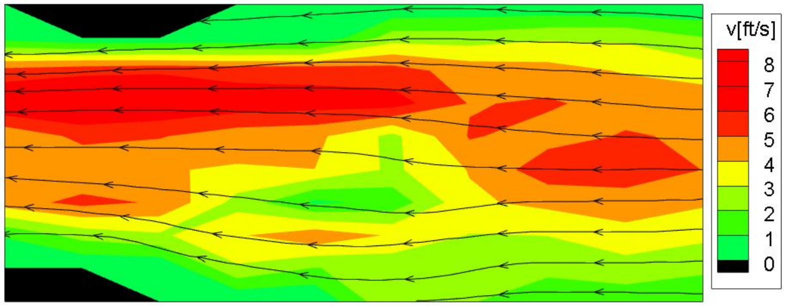

Figure F- 67 TecPlot output for velocity at 600 cfs at the large rock upstream "V", low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

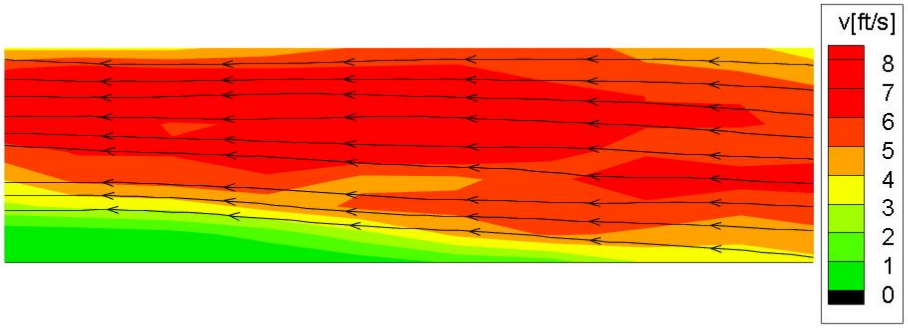

Figure F-67. TecPlot output for velocity at 600 cfs at the small rock upstream "V", very low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

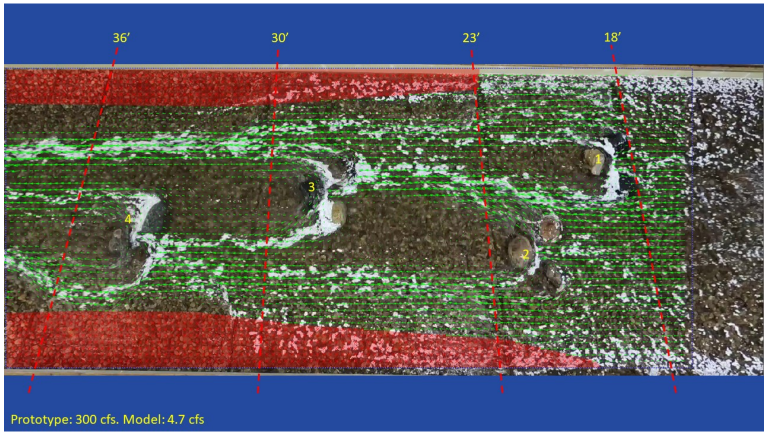

Figure F-68. PIVLab output of velocity vectors at 300 cfs at the large rock downstream “V”, high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines and rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

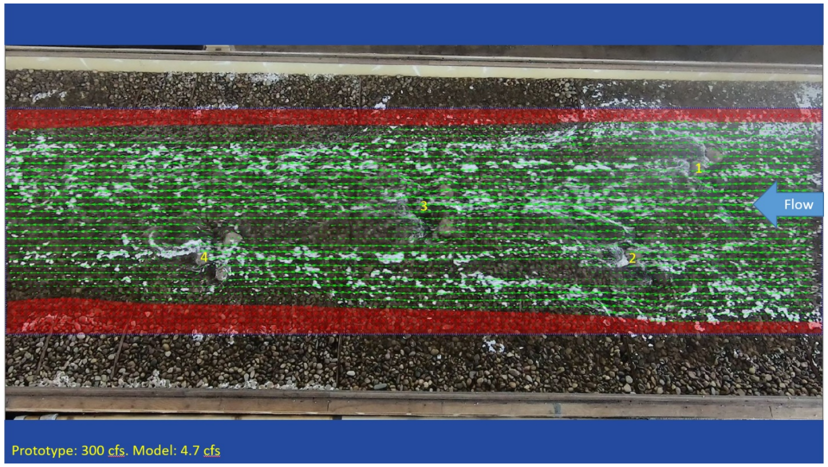

Figure F-70. PIVLab output of velocity vectors at 300 cfs at the small rock downstream “V”, high density configuration through the channel. Rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

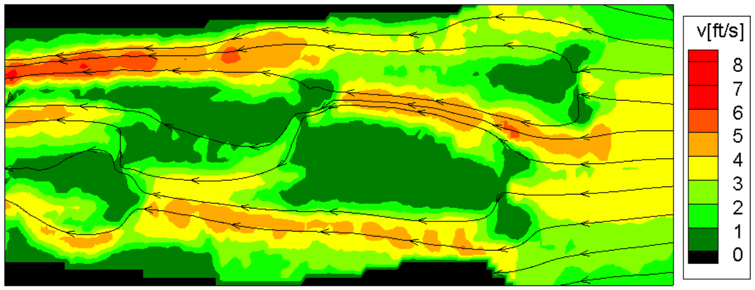

Figure F-69. TecPlot output for velocity at 300 cfs at the large rock downstream “V”, high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

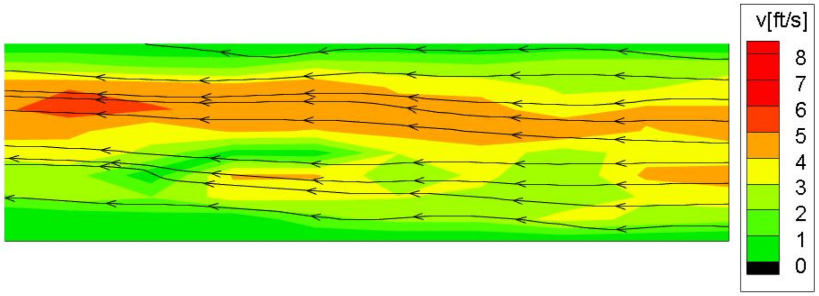

Figure F-71. TecPlot output for velocity at 300 cfs at the small rock downstream “V”, high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

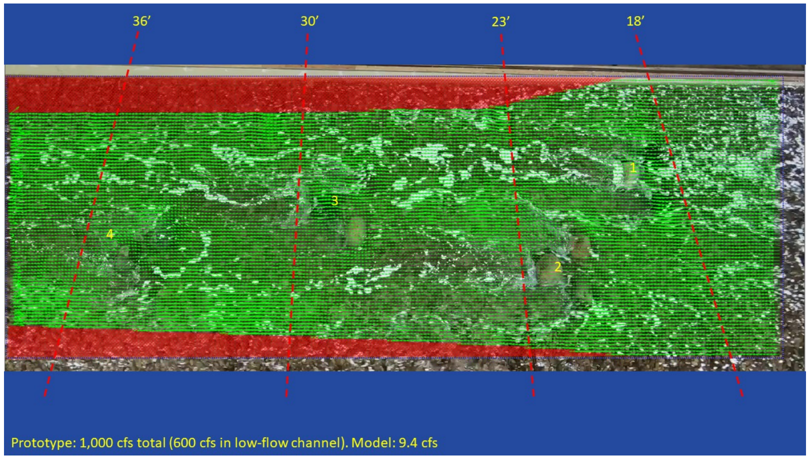

Figure F-72. PIVLab output of velocity vectors at 600 cfs at the large rock downstream "V", high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

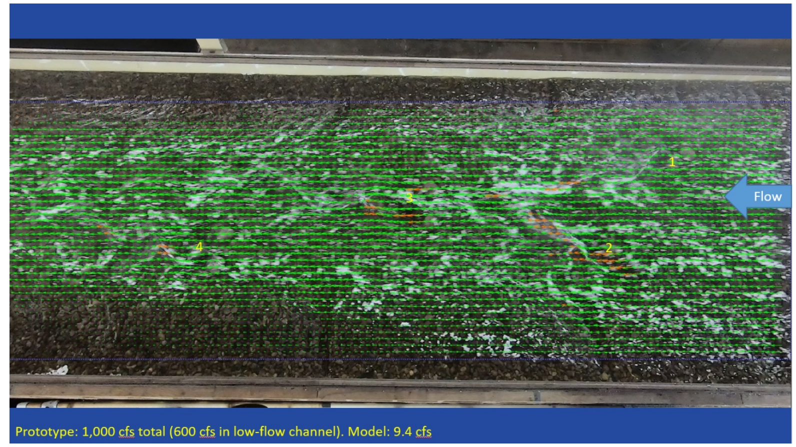

Figure F-74. PIVLab output of velocity vectors at 600 cfs at the small rock downstream "V", high density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

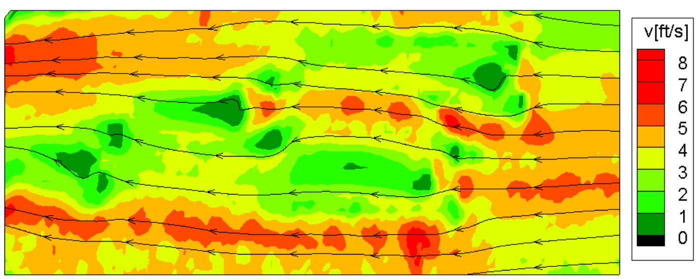

Figure F-73. TecPlot output for velocity at 600 cfs at the large rock downstream "V", high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

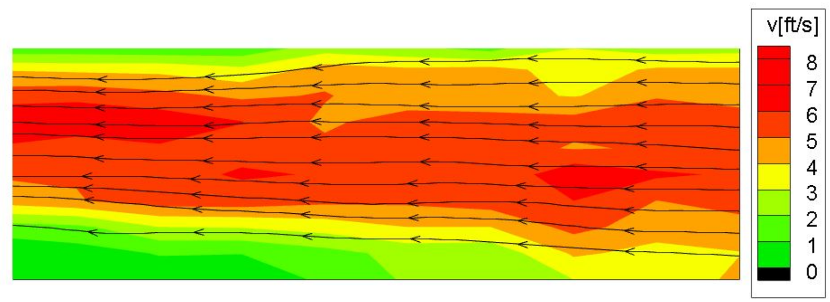

Figure F-75. TecPlot output for velocity at 600 cfs at the small rock downstream "V", high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

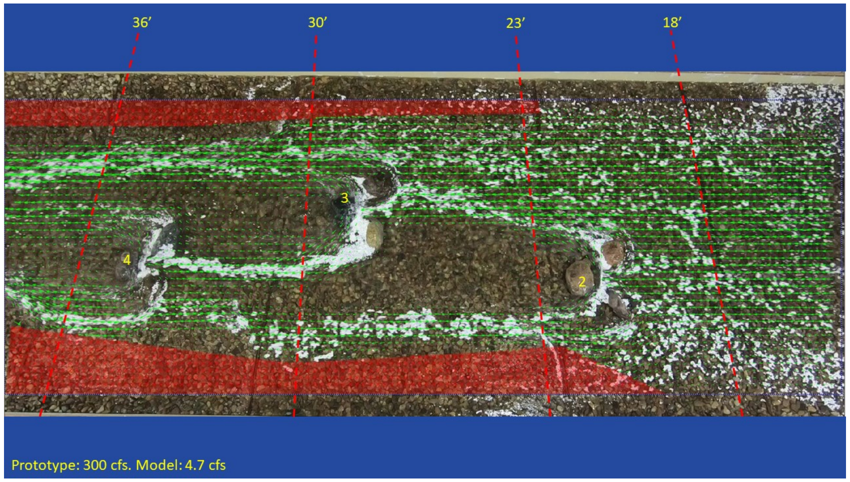

Figure F-76. PIVLab output of velocity vectors at 300 cfs at the large rock downstream "V", medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

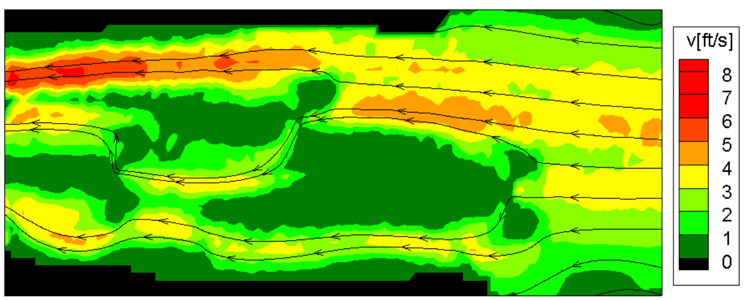

Figure F-77. TecPlot output for velocity at 300 cfs at the large rock downstream "V", medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

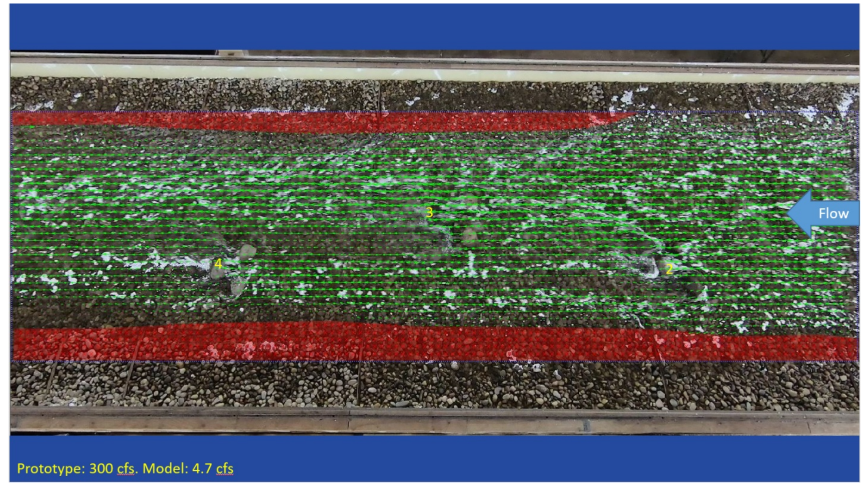

Figure F-78. PIVLab output of velocity vectors at 300 cfs at the small rock downstream "V", medium density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

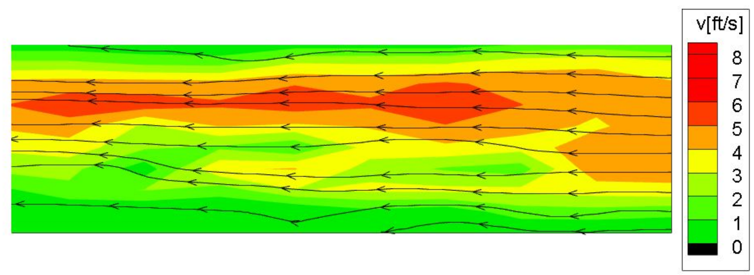

Figure F-79. TecPlot output for velocity at 300 cfs at the small rock downstream "V", medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

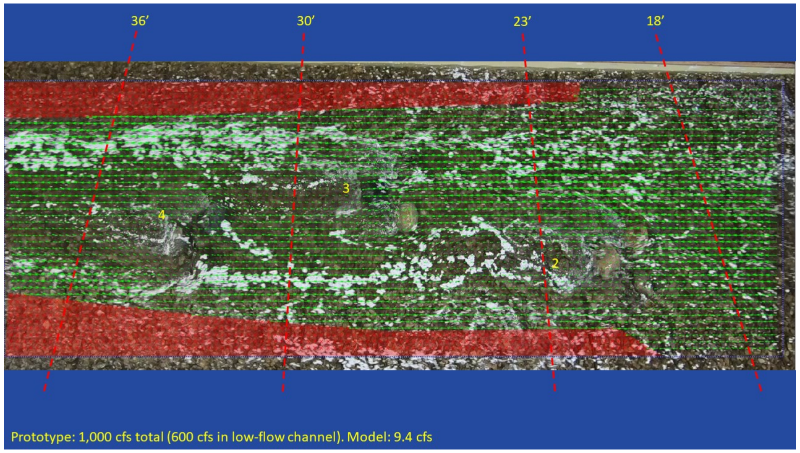

Figure F-80. PIVLab output of velocity vectors at 600 cfs at the large rock downstream "V", medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

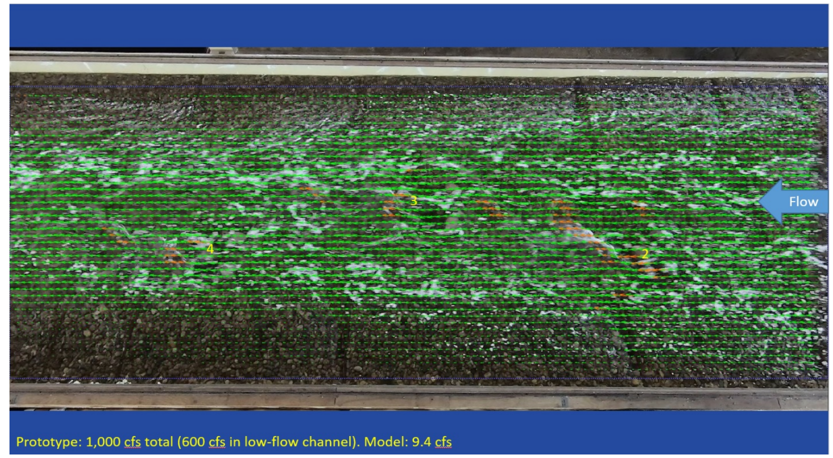

Figure F-82. PIVLab output of velocity vectors at 600 cfs at the small rock downstream "V", medium density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

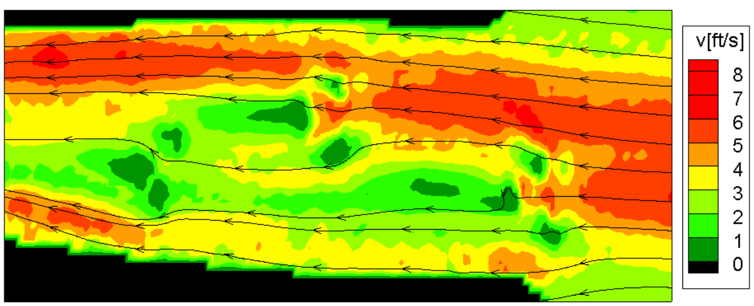

Figure F-81. TecPlot output for velocity at 600 cfs at the large rock downstream "V", medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

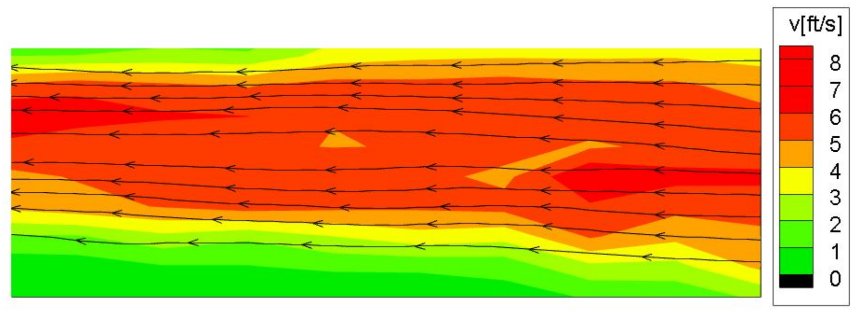

Figure F-83. TecPlot output for velocity at 600 cfs at the small rock downstream "V", medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

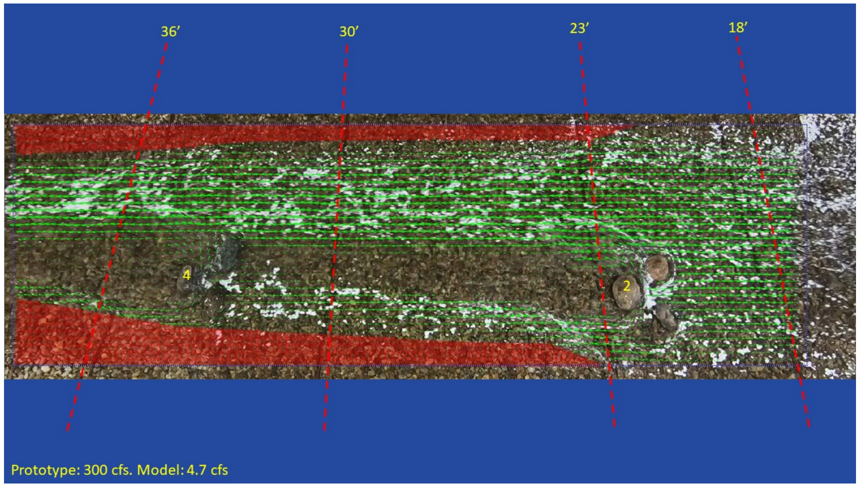

Figure F-84. PIVLab output of velocity vectors at 300 cfs at the large rock downstream "V", low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

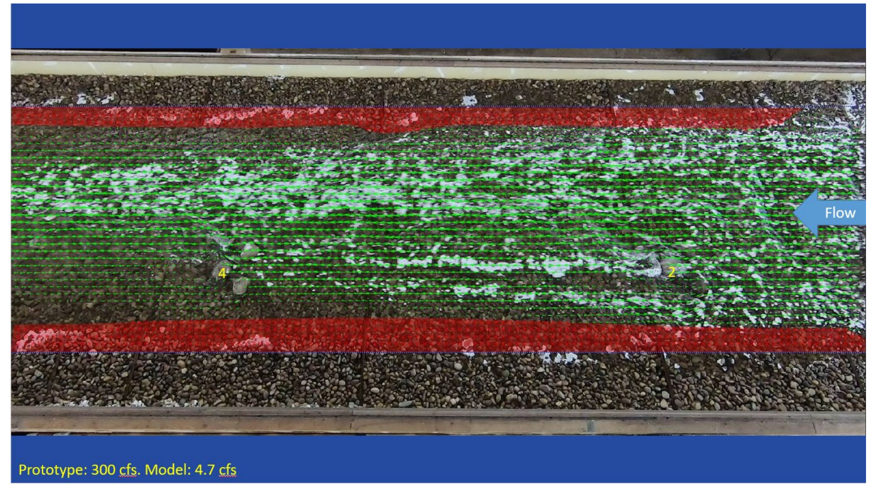

Figure F- 86 PIVLab output of velocity vectors at 300 cfs at the small rock downstream "V", low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

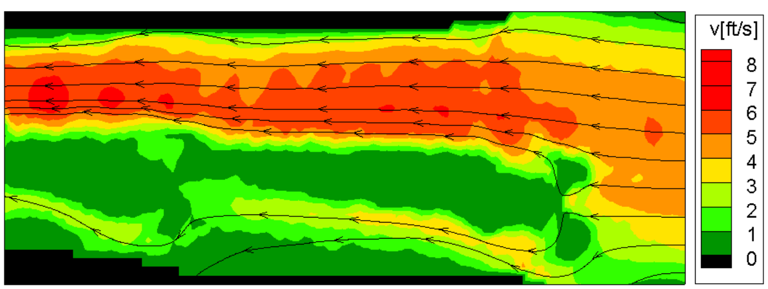

Figure F-85. TecPlot output for velocity at 300 cfs at the large rock downstream "V", low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

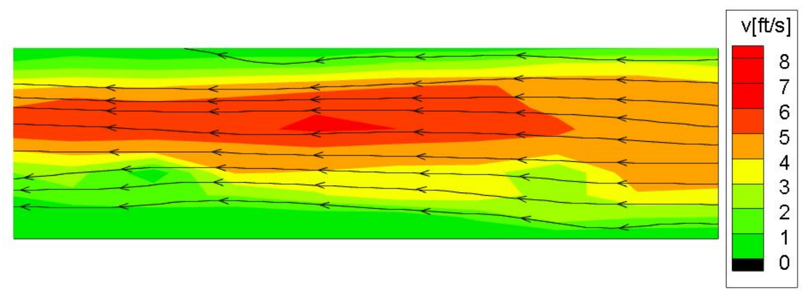

Figure F- 87 TecPlot output for velocity at 300 cfs at the small rock downstream "V", low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

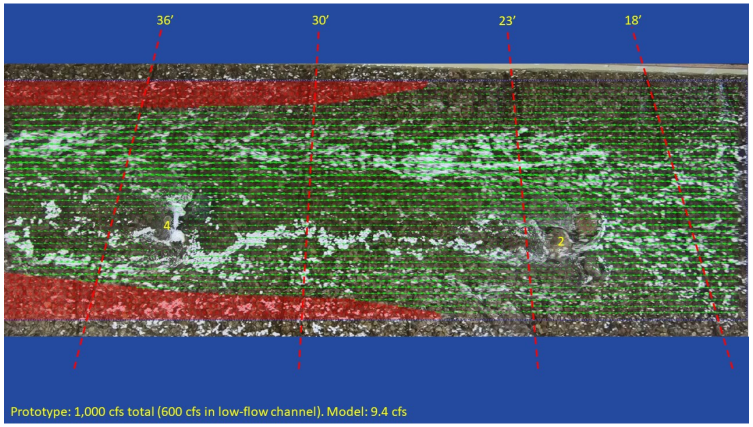

Figure F-86. PIVLab output of velocity vectors at 600 cfs at the large rock downstream "V", low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

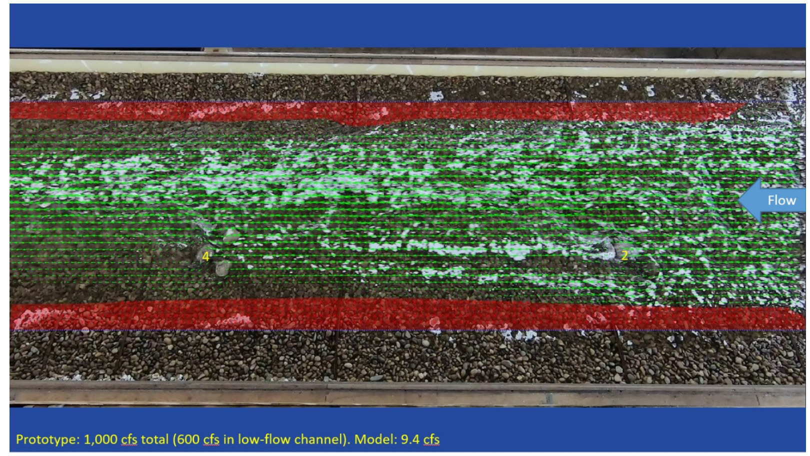

Figure F-88. PIVLab output of velocity vectors at 600 cfs at the small rock downstream "V", low density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

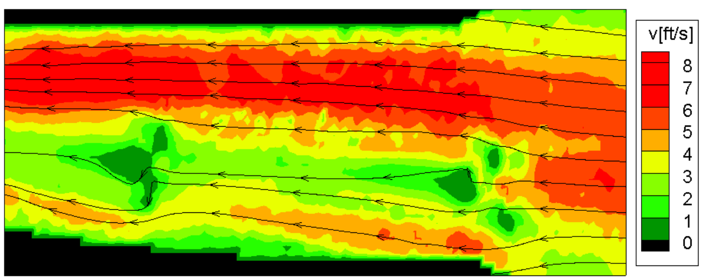

Figure F-87. TecPlot output for velocity at 600 cfs at the large rock downstream "V", low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

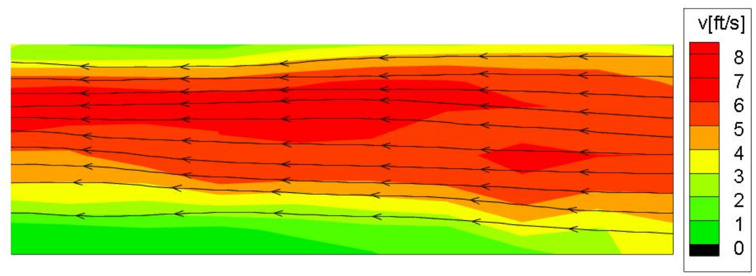

Figure F-89. TecPlot output for velocity at 600 cfs at the small rock downstream "V", low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

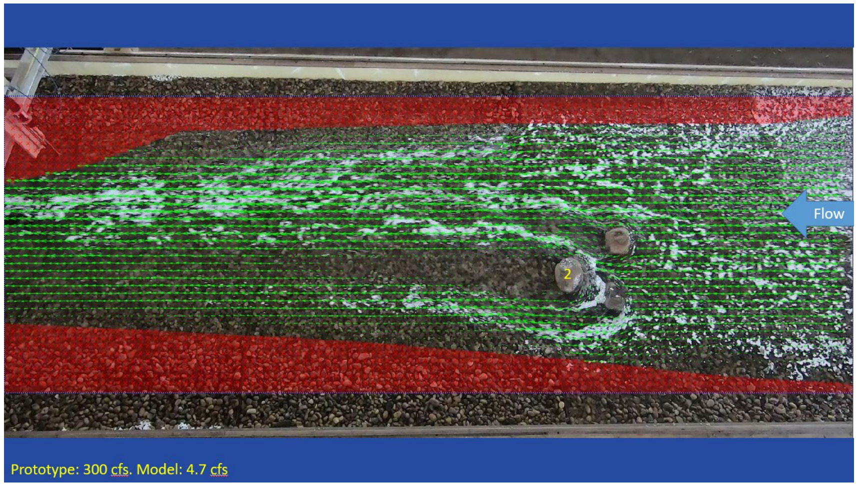

Figure F- 92 PIVLab output of velocity vectors at 300 cfs at the large rock downstream "V", very low density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

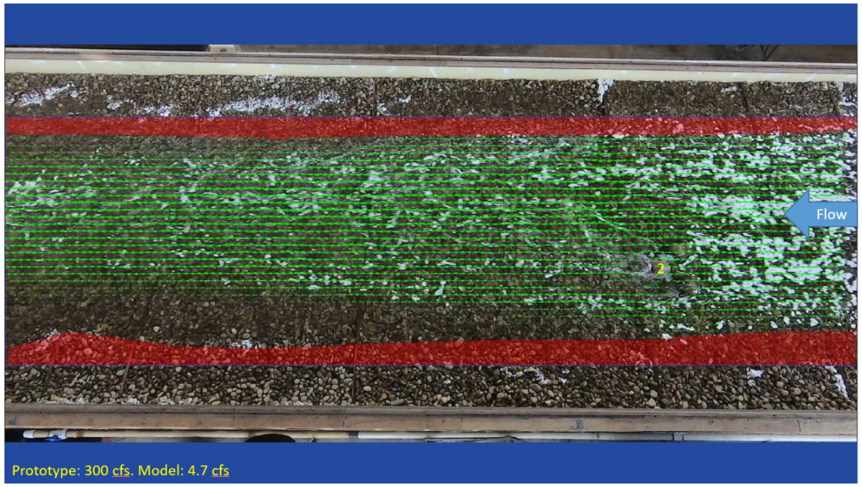

Figure F-94. PIVLab output of velocity vectors at 300 cfs at the small rock downstream "V", very low density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

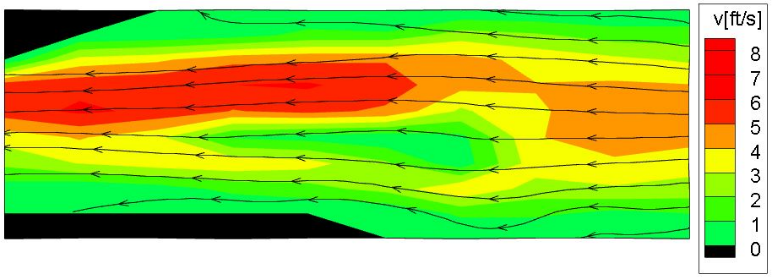

Figure F- 93 TecPlot output for velocity at 300 cfs at the large rock downstream "V", very low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

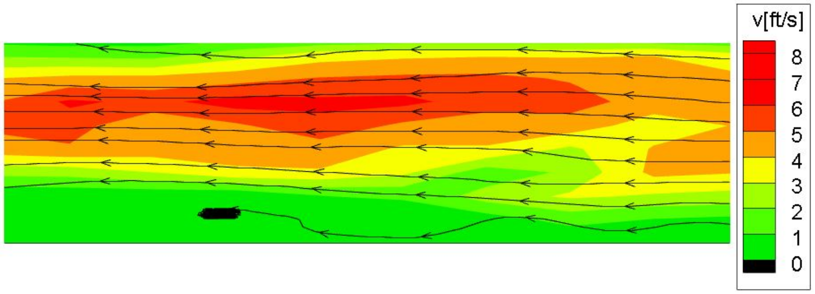

Figure F-95. TecPlot output for velocity at 300 cfs at the small rock downstream "V", very low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

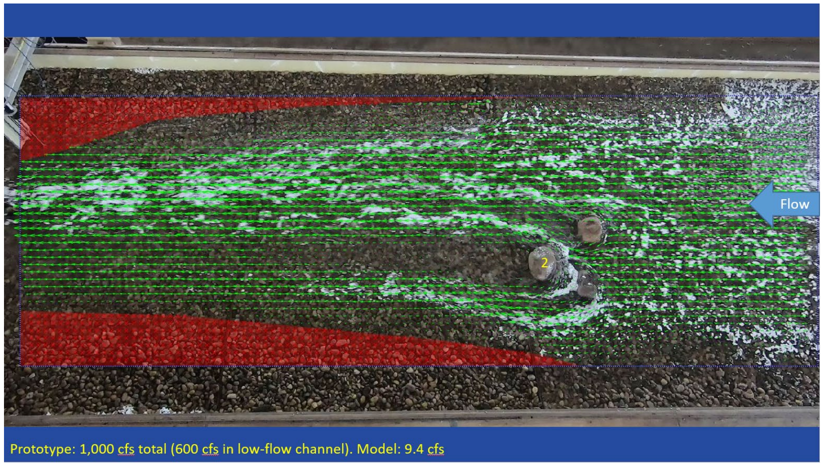

Figure F- 96 PIVLab output of velocity vectors at 600 cfs at the large rock downstream "V", very low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. portions that are either too shallow or too reflective for analysis in PIVLab.

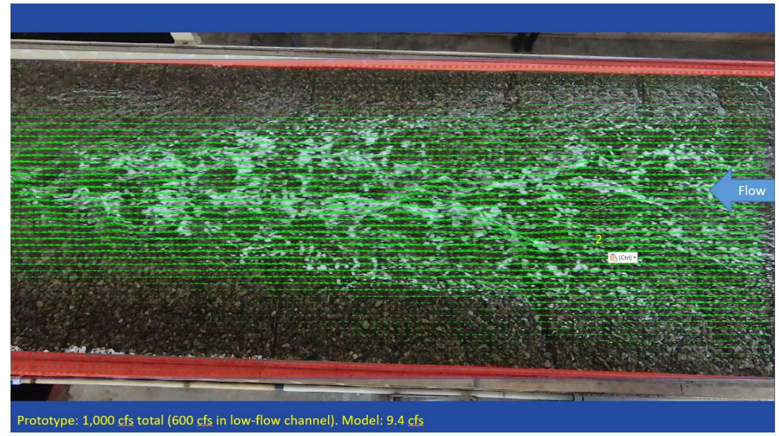

Figure F-908. PIVLab output of velocity vectors at 600 cfs at the small rock downstream "V", very low density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

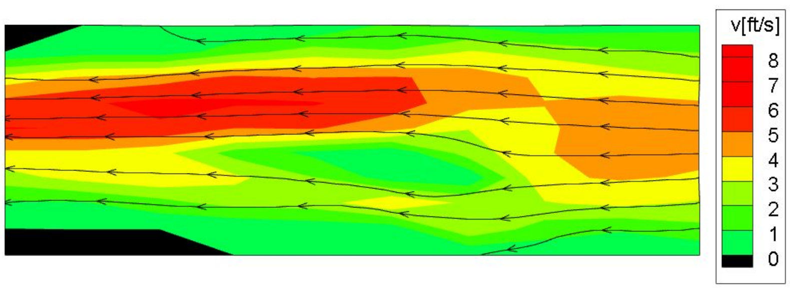

Figure F- 97 TecPlot output for velocity at 600 cfs at the large rock downstream "V", very low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

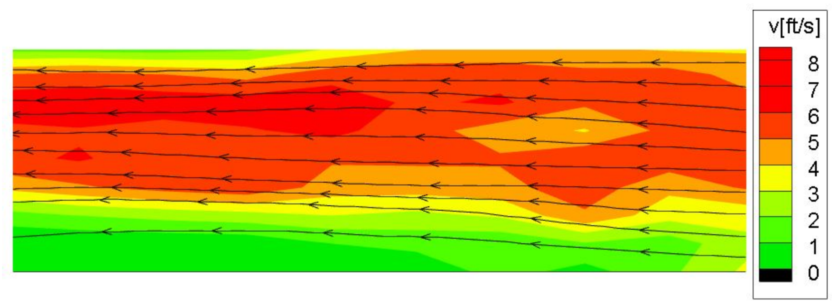

Figure F-919. TecPlot output for velocity at 600 cfs at the small rock downstream "V", very low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

Large Rock- Diamond Configuration (all flow rates)

The diamond configuration was only performed for the large rocks. Thus, it is listed separately.

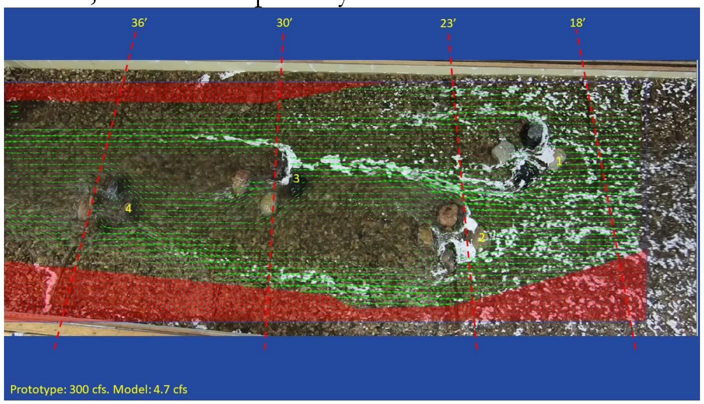

Figure F-100. PIVLab output of velocity vectors at 300 cfs at the large rock diamond, high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

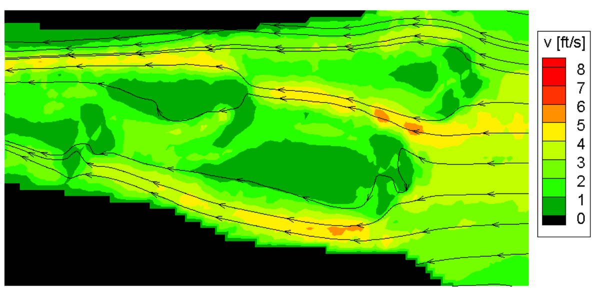

Figure F-101. TecPlot output for velocity at 300 cfs at the large rock diamond, high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

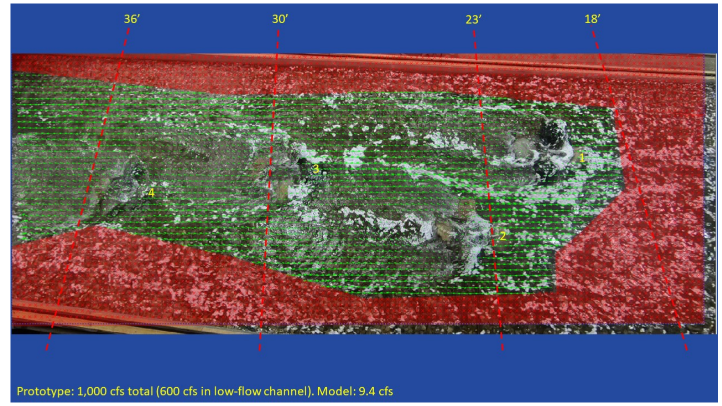

Figure F-102. PIVLab output of velocity vectors at 600 cfs at the large rock diamond, high density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

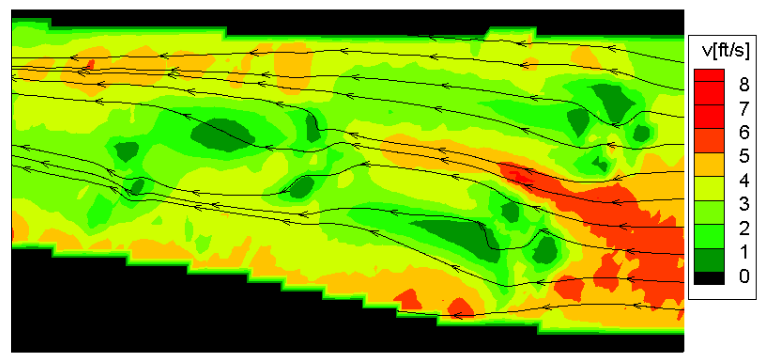

Figure F-103. TecPlot output for velocity at 600 cfs at the large rock diamond, high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

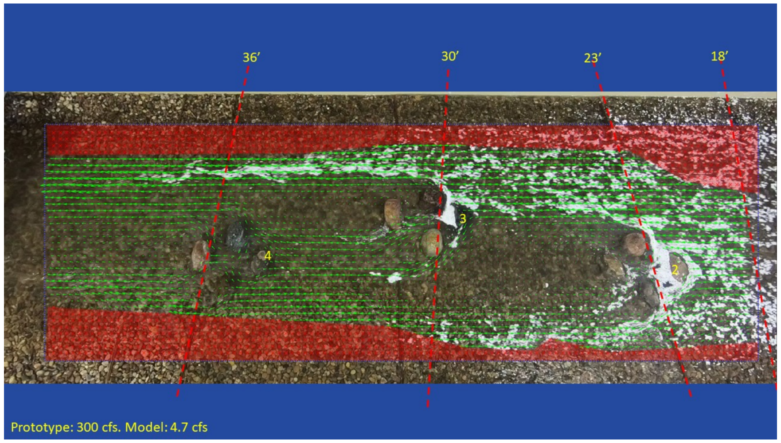

Figure F-9204. PIVLab output of velocity vectors at 300 cfs at the large rock diamond, medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

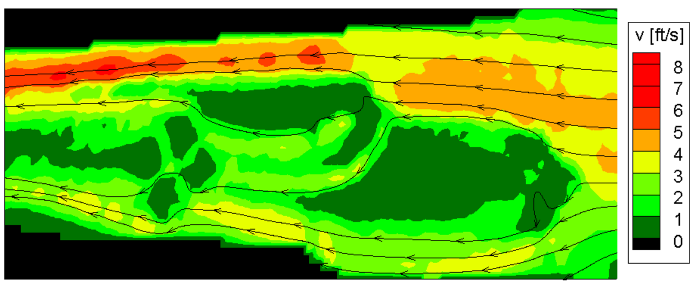

Figure F-105. TecPlot output for velocity at 300 cfs at the large rock diamond, medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

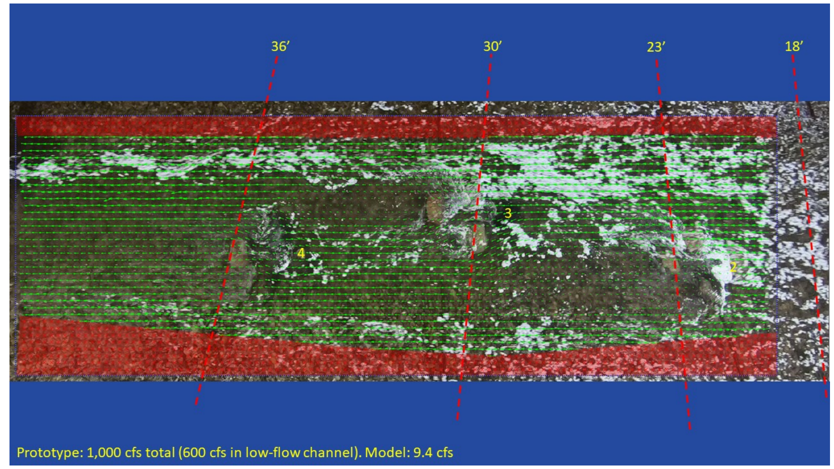

Figure F-106. PIVLab output of velocity vectors at 600 cfs at the large rock diamond, medium density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

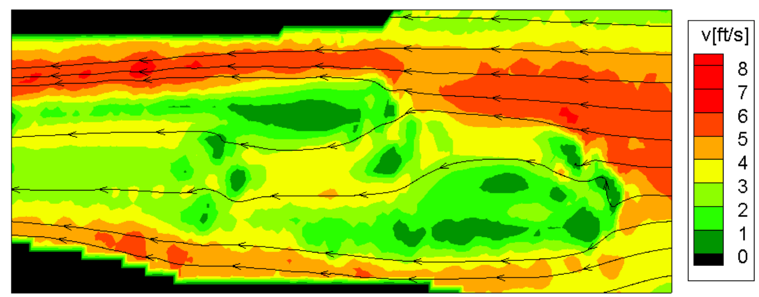

Figure F-9307. TecPlot output for velocity at 600 cfs at the large rock diamond, medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

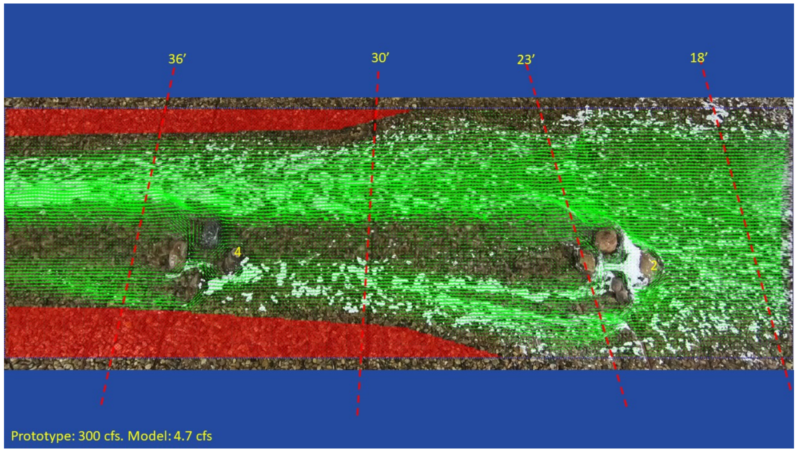

Figure F-948. PIVLab output of velocity vectors at 300 cfs at the large rock diamond, low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines and rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

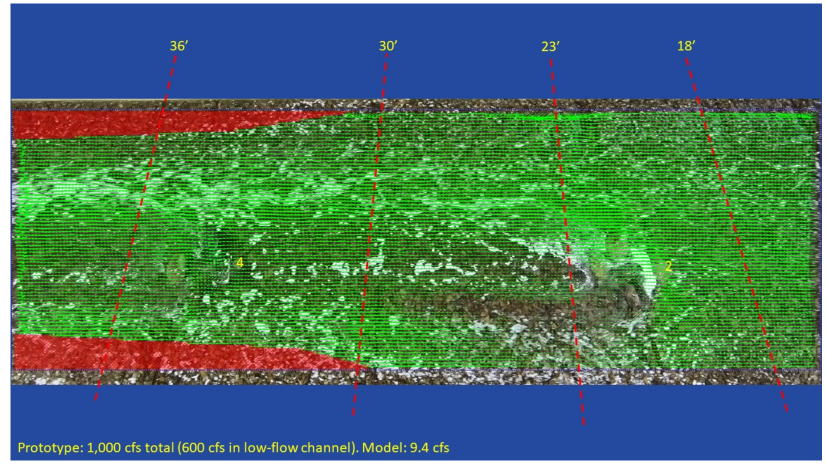

Figure F-110. PIVLab output of velocity vectors at 600 cfs at the large rock diamond, low density configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines and rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

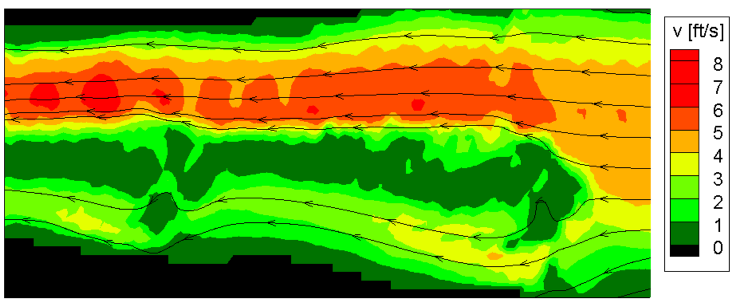

Figure F-109. TecPlot output for velocity at 300 cfs at the large rock diamond, low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

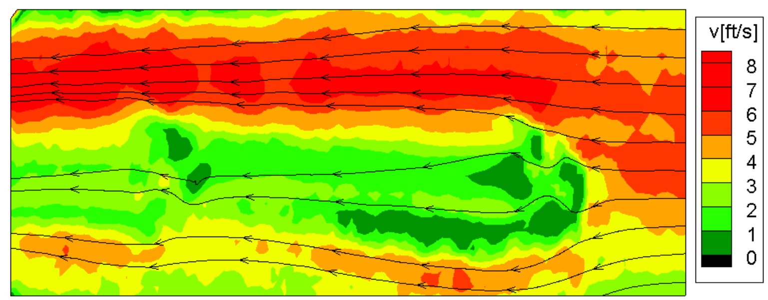

Figure F-9511. TecPlot output for velocity at 600 cfs at the large rock diamond, low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

Small Rock- 2.3 cfs configurations

The 2.3cfs (150 cfs, prototype) flow rate was only performed for the small rocks. Thus, it is listed separately.

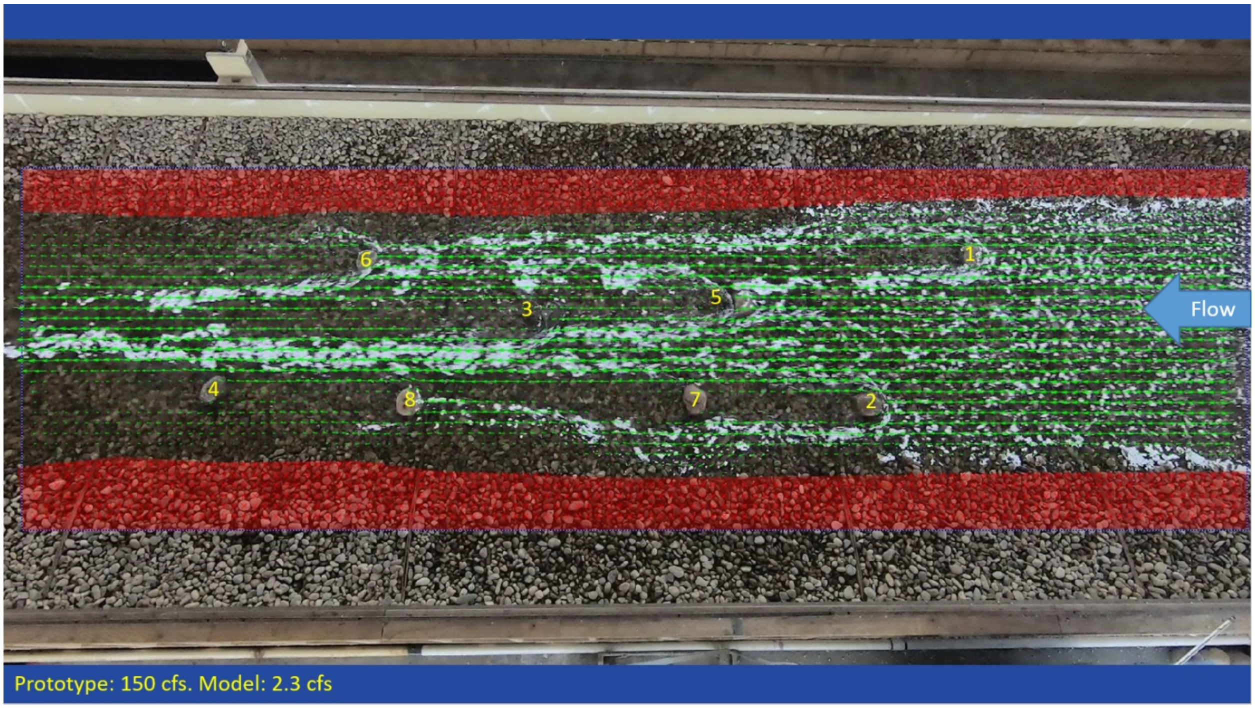

Figure F-96. PIVLab output of velocity vectors at 150 cfs at the single small rock, high density configuration through the channel. Rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

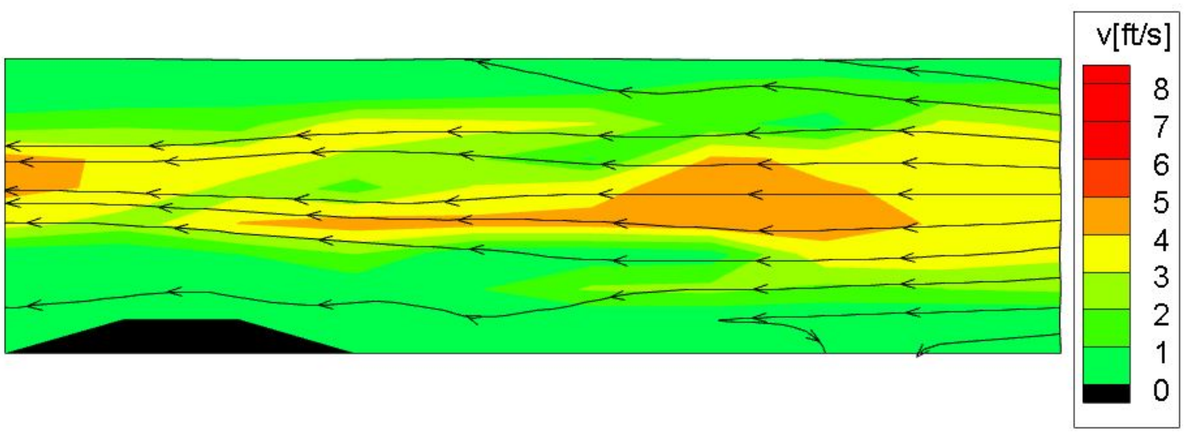

Figure F-97. TecPlot output for velocity at 150 cfs at the single small rock, high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

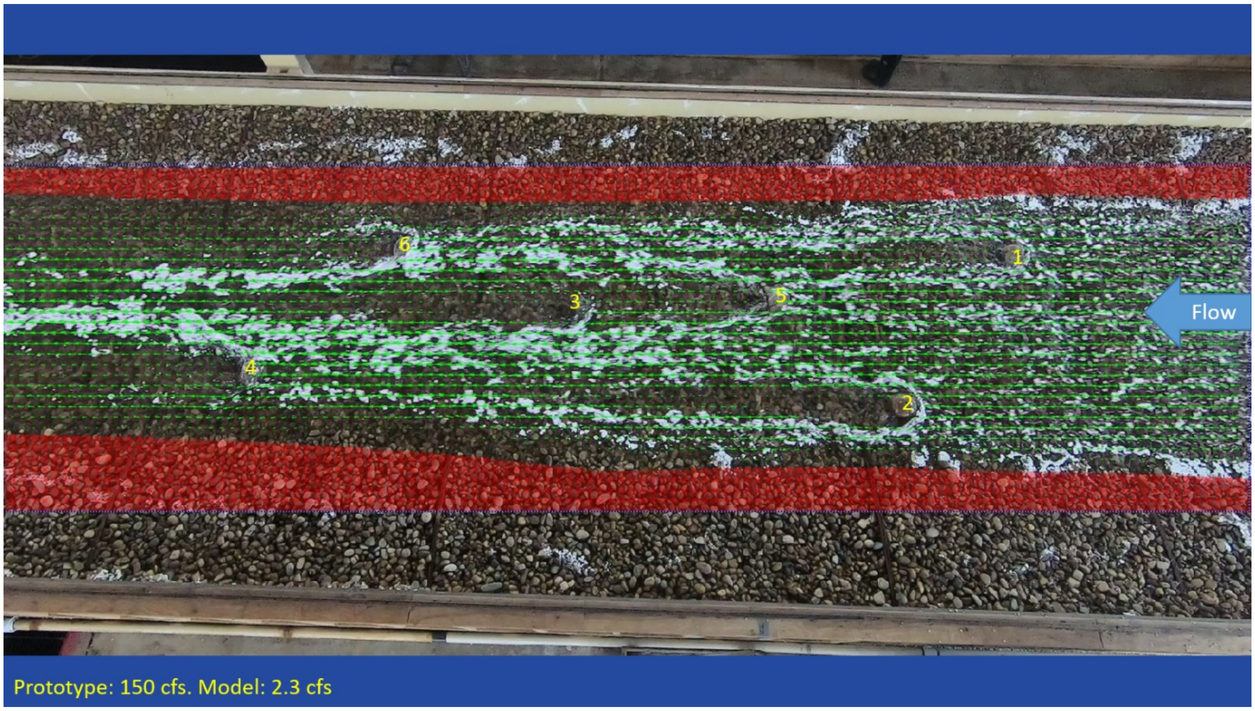

Figure F-98. PIVLab output of velocity vectors at 150 cfs at the single small rock, medium-high density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

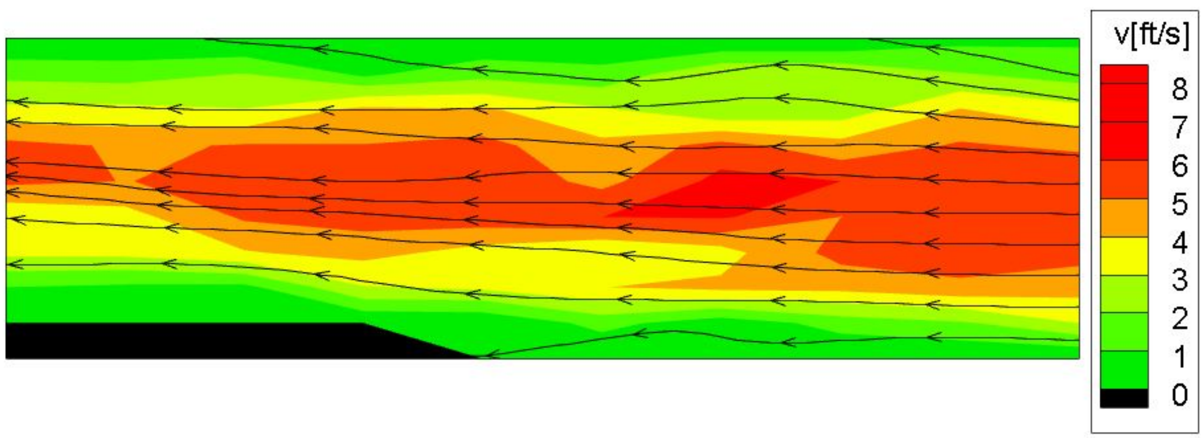

Figure F-99. TecPlot output for velocity at 150 cfs at the single small rock, medium-high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

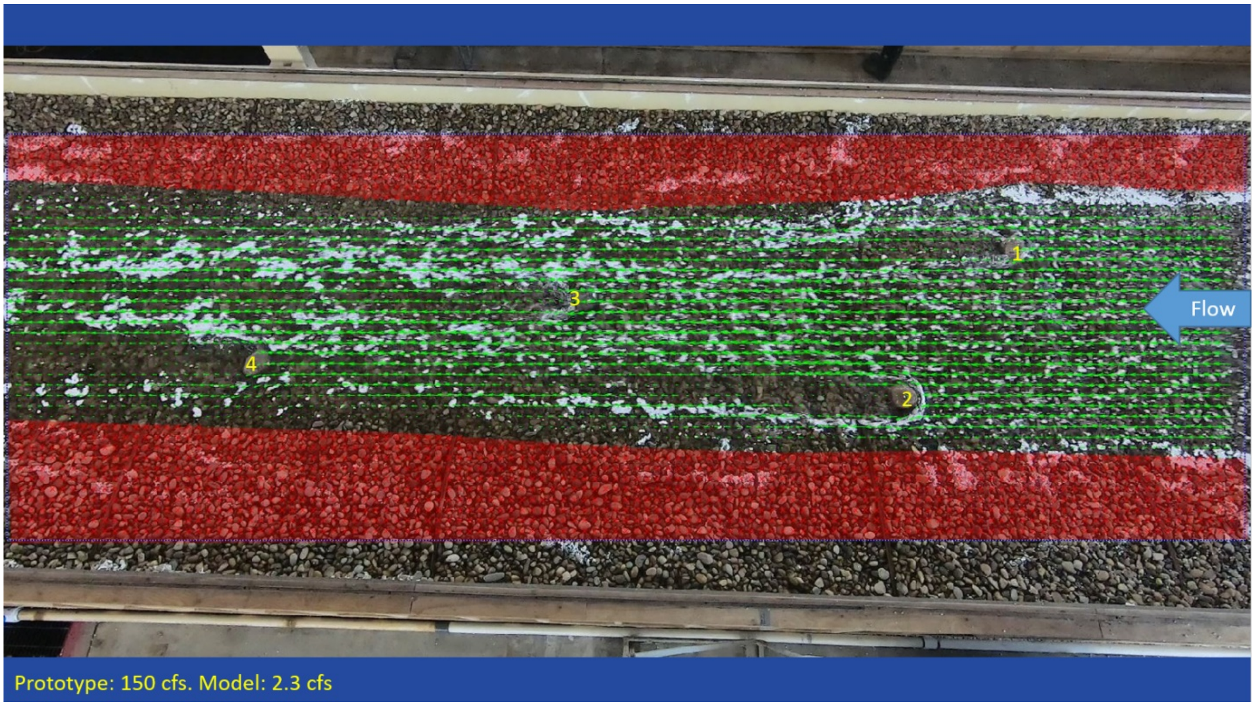

Figure F-100. PIVLab output of velocity vectors at 150 cfs at the single small rock, medium density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

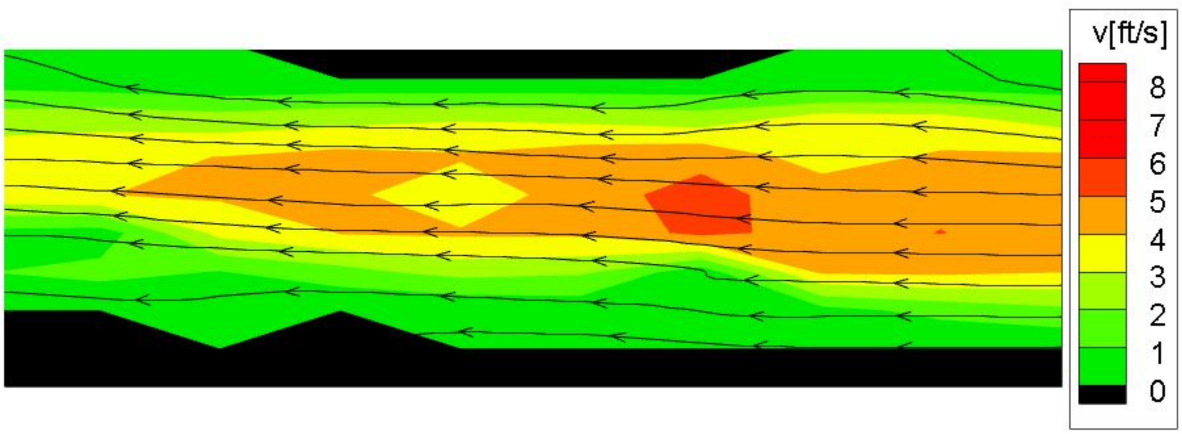

Figure F-101. TecPlot output for velocity at 150 cfs at the single small rock, medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

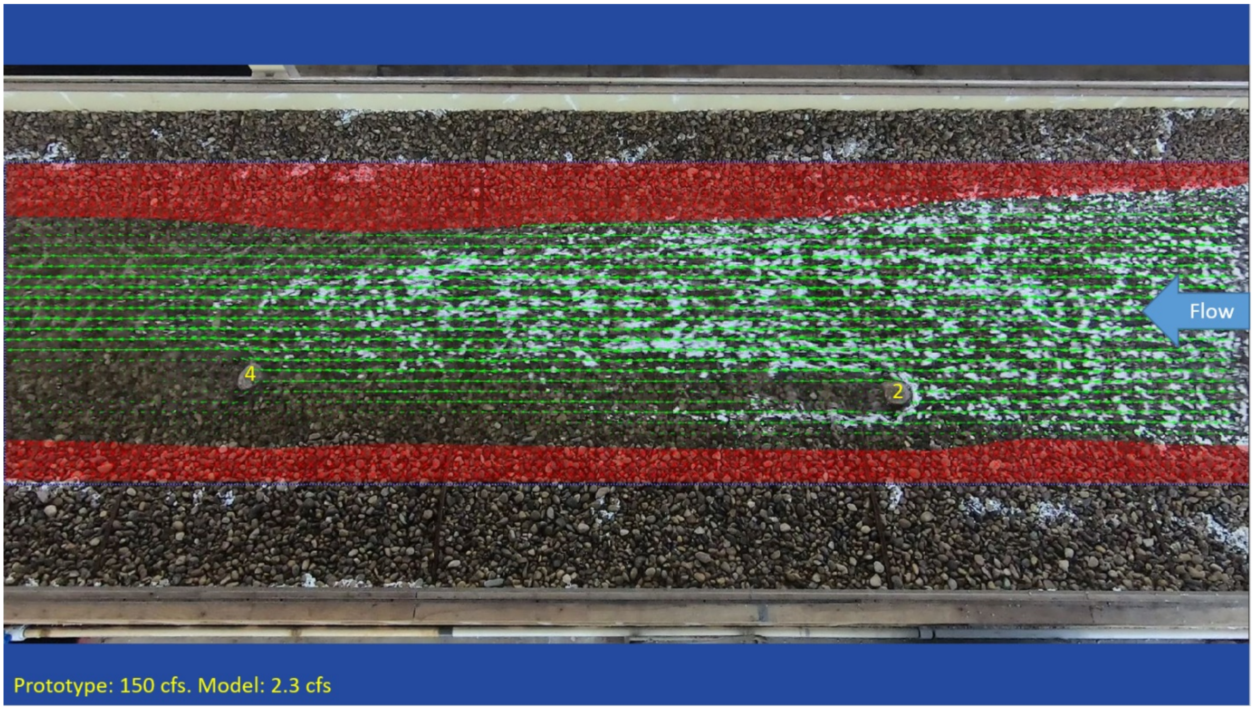

Figure F-102. PIVLab output of velocity vectors at 150 cfs at the single small rock, low density configuration through the channel. Rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

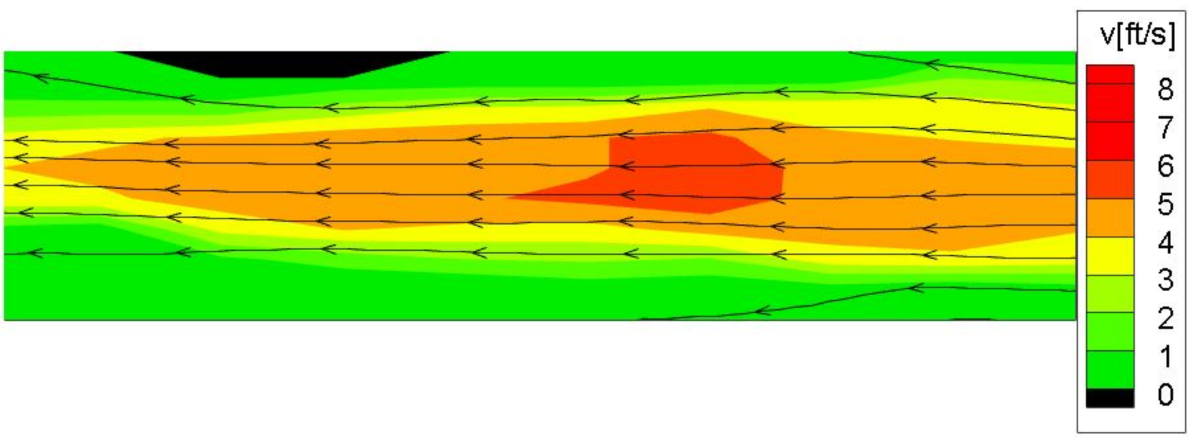

Figure F-103. TecPlot output for velocity at 150 cfs at the single small rock, low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

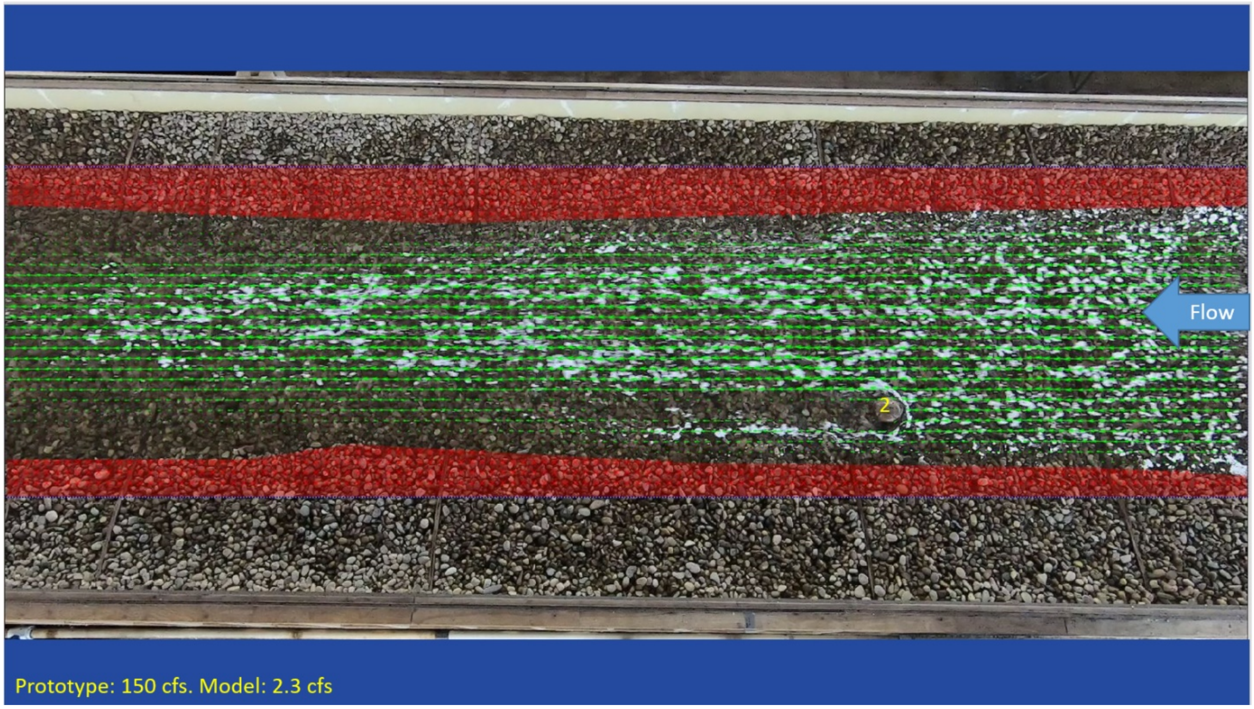

Figure F-104. PIVLab output of velocity vectors at 150 cfs at the single small rock, very low density configuration through the channel. Rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

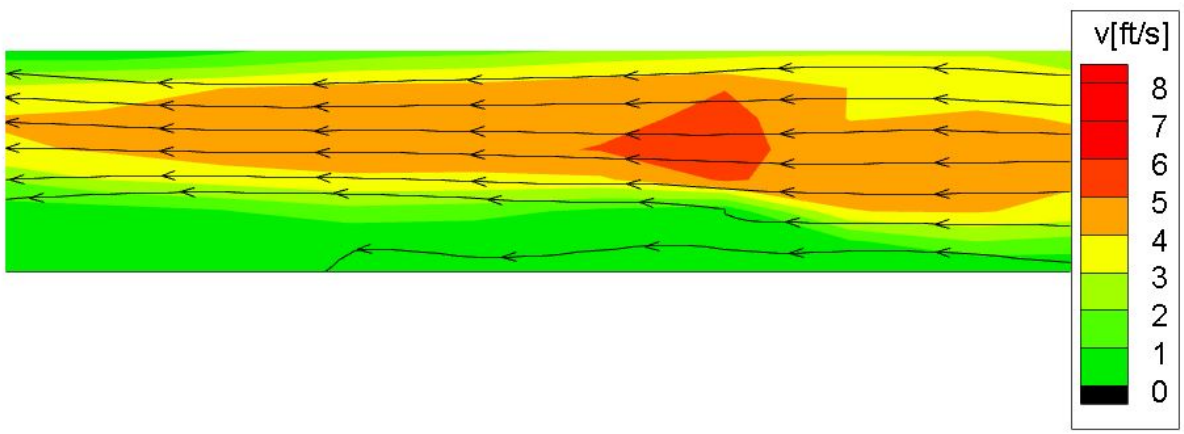

Figure F-105. TecPlot output for velocity at 150 cfs at the single small rock, very low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

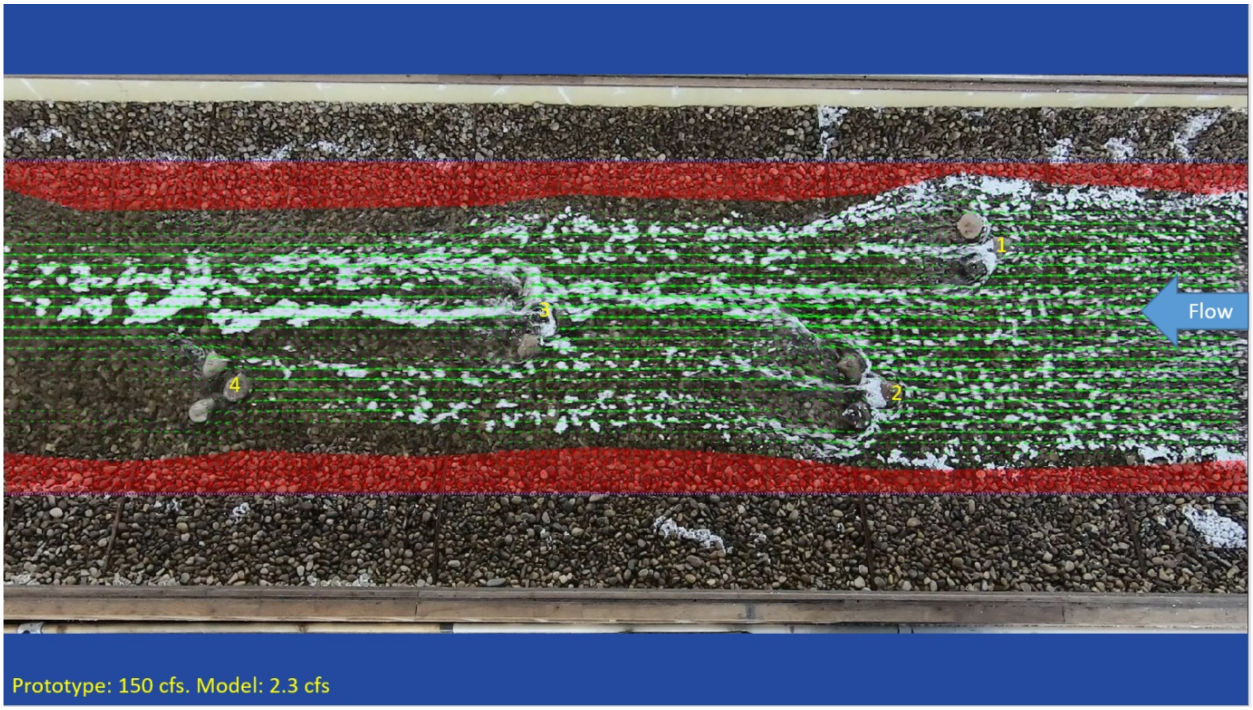

Figure F-106. PIVLab output of velocity vectors at 150 cfs at the small rock upstream "V", high density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

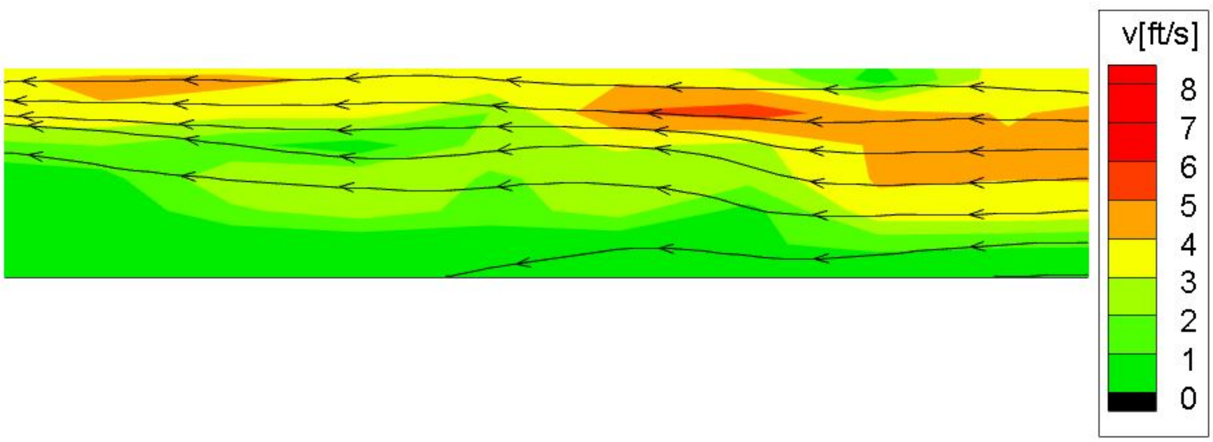

Figure F-107. TecPlot output for velocity at 150 cfs at the small rock upstream "V", high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

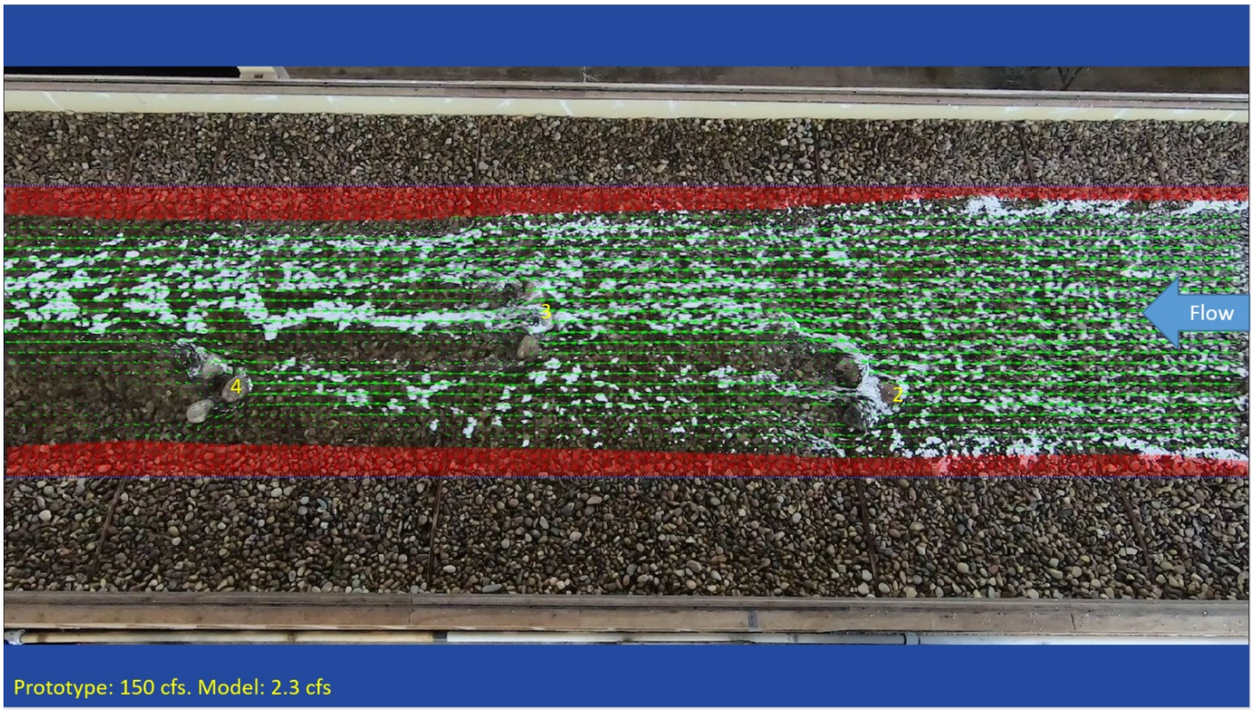

Figure F-108. PIVLab output of velocity vectors at 150 cfs at the small rock upstream "V", medium density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

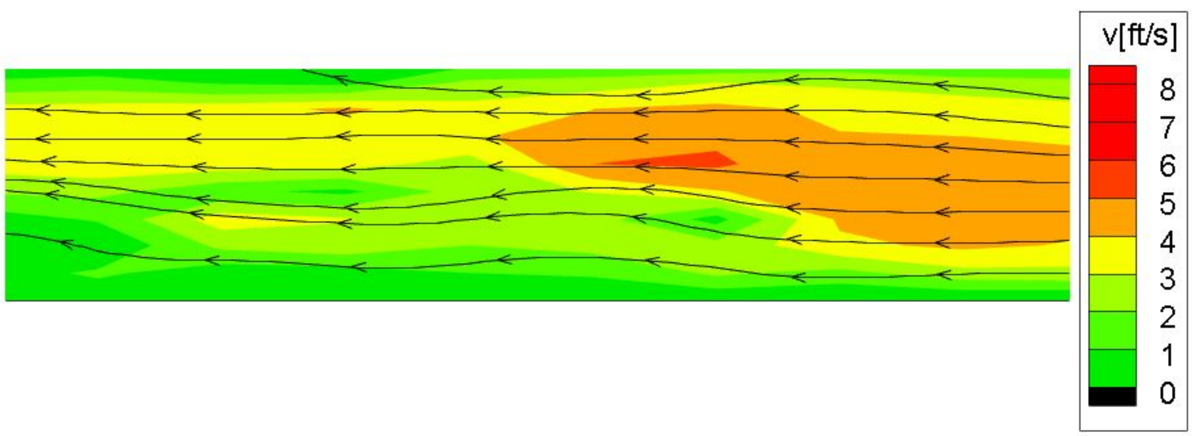

Figure F-109. TecPlot output for velocity at 150 cfs at the small rock upstream "V", medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

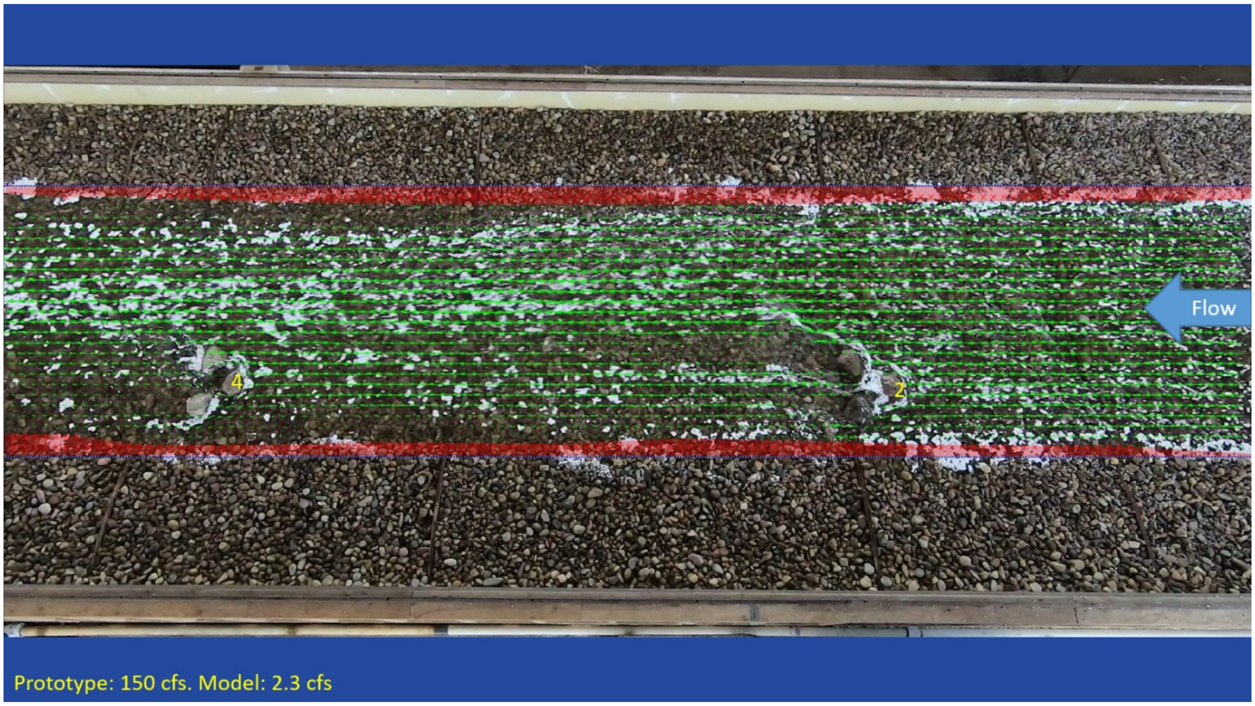

Figure F-110. PIVLab output of velocity vectors at 150 cfs at the small rock upstream "V", low density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

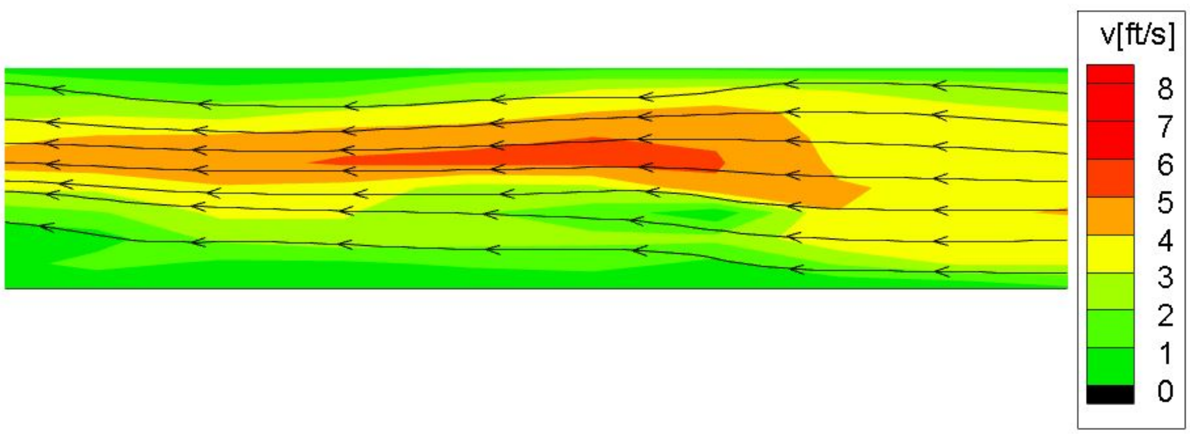

Figure F-111. TecPlot output for velocity at 150 cfs at the small rock upstream "V", low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

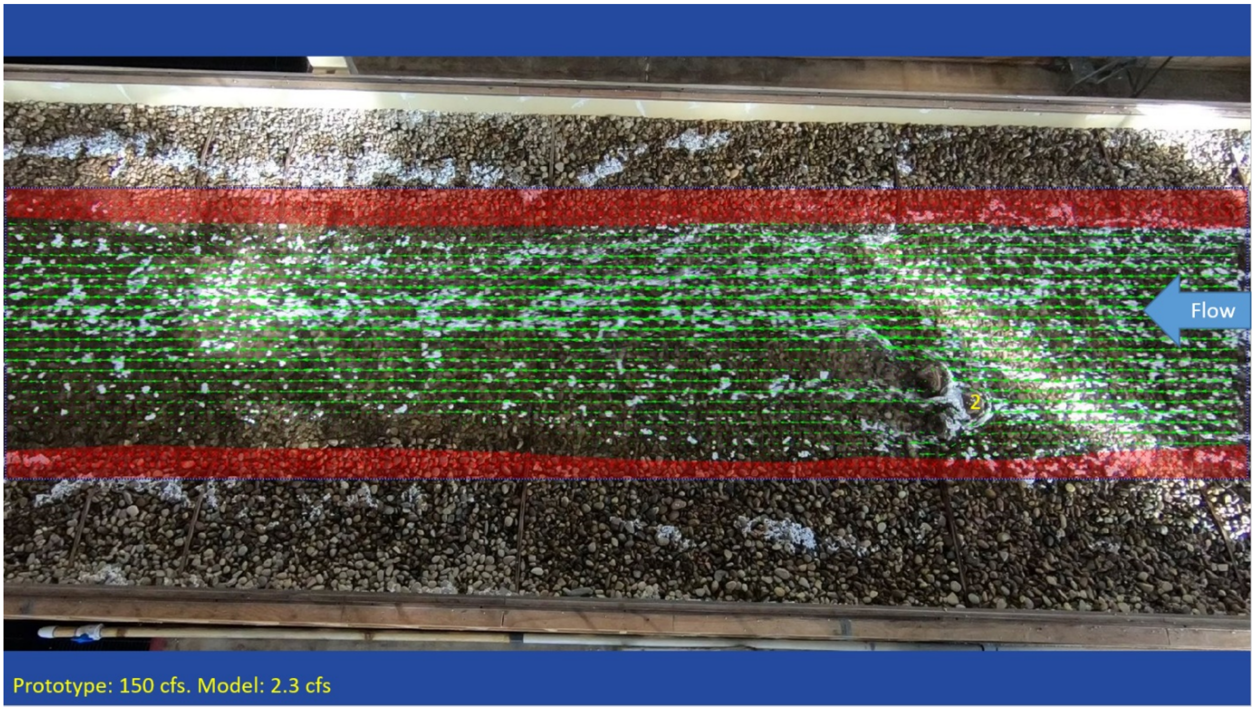

Figure F-112. PIVLab output of velocity vectors at 150 cfs at the small rock upstream "V", very low density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

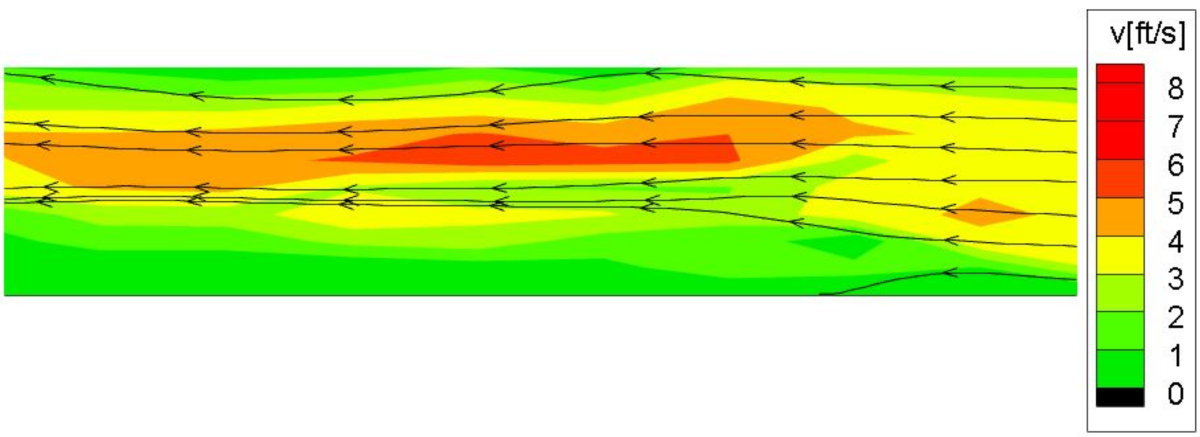

Figure F-113. TecPlot output for velocity at 150 cfs at the small rock upstream "V", very low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

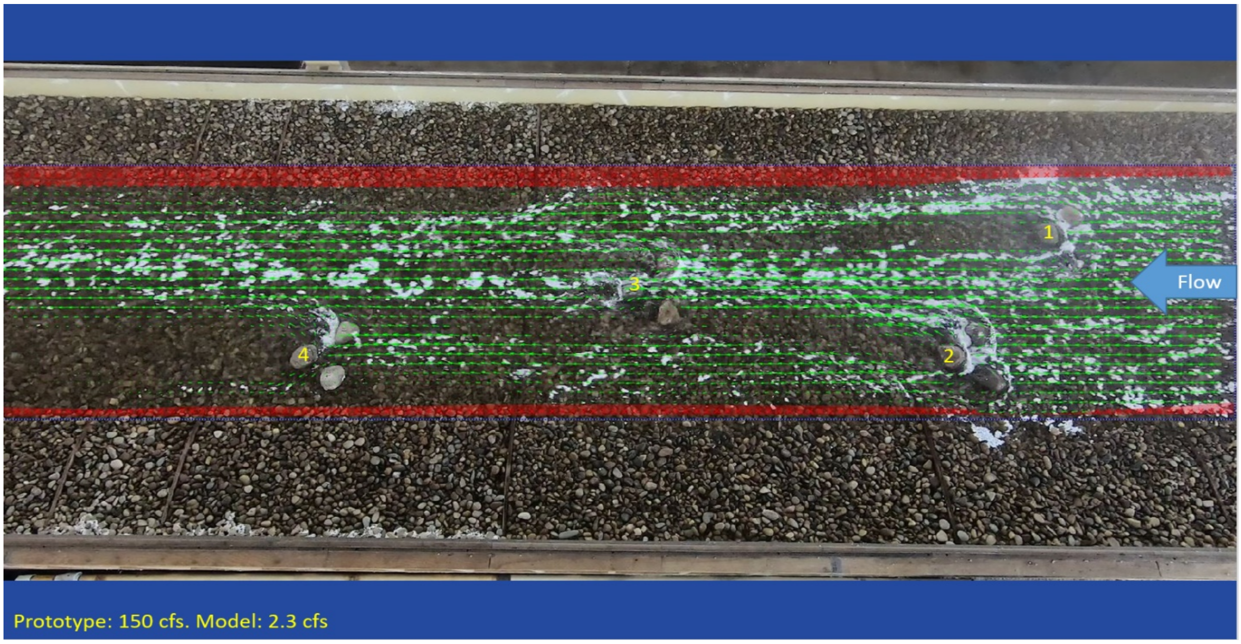

Figure F-114. PIVLab output of velocity vectors at 150 cfs at the small rock downstream "V", high density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

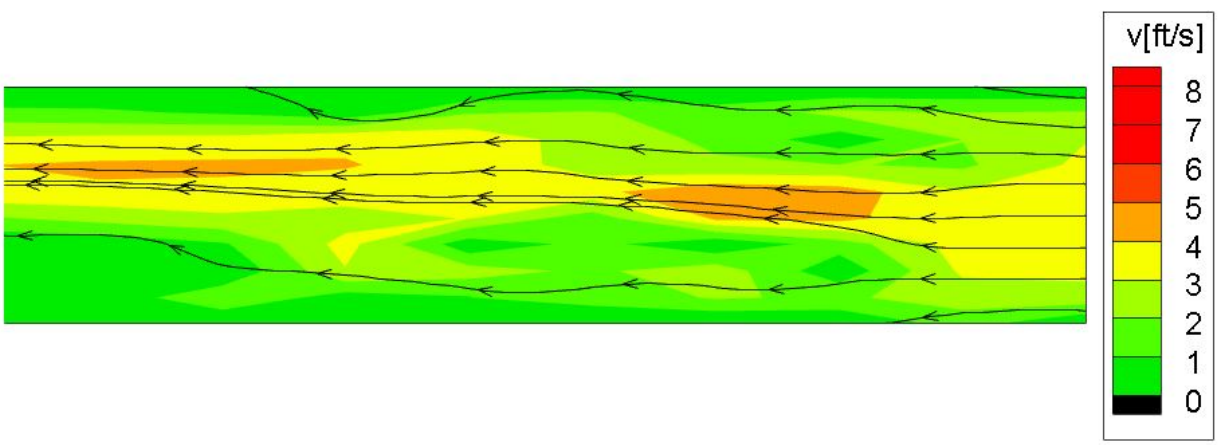

Figure F-115. TecPlot output for velocity at 150 cfs at the small rock downstream "V", high density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

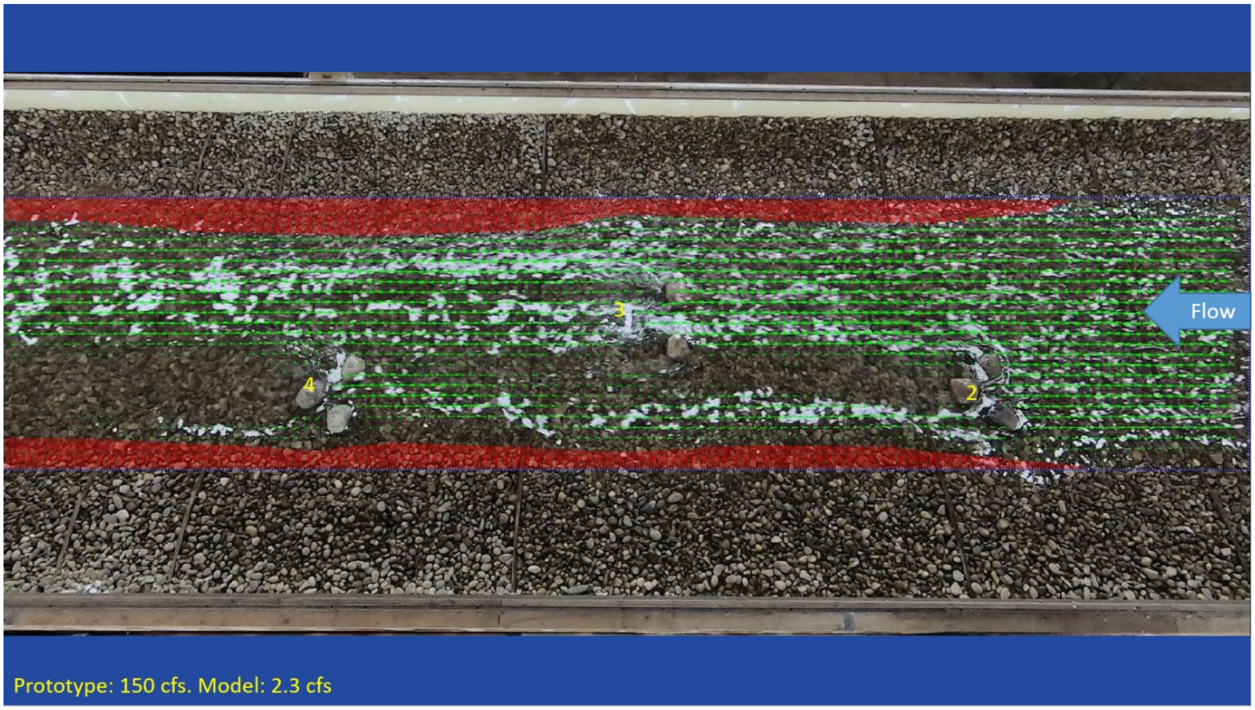

Figure F-116. PIVLab output of velocity vectors at 150 cfs at the small rock downstream "V", medium density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

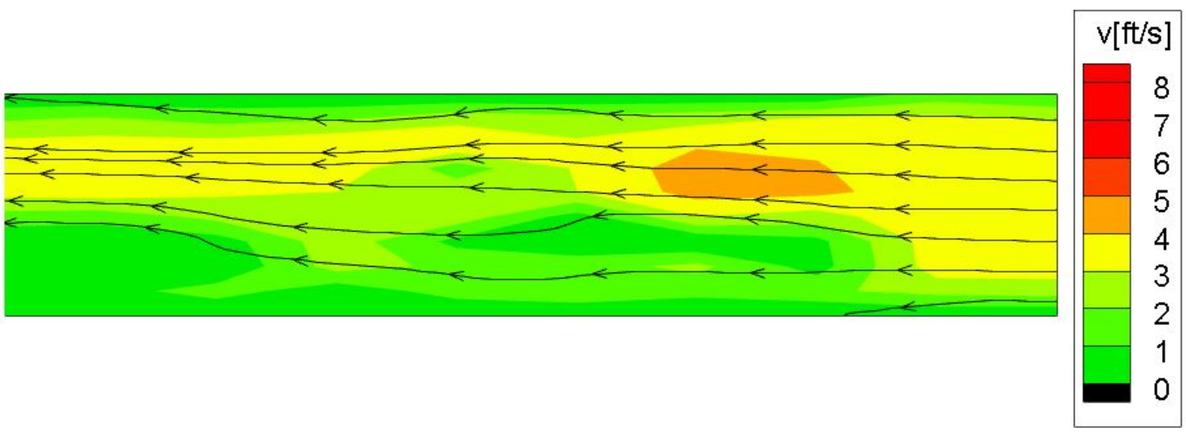

Figure F-117. TecPlot output for velocity at 150 cfs at the small rock downstream "V", medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

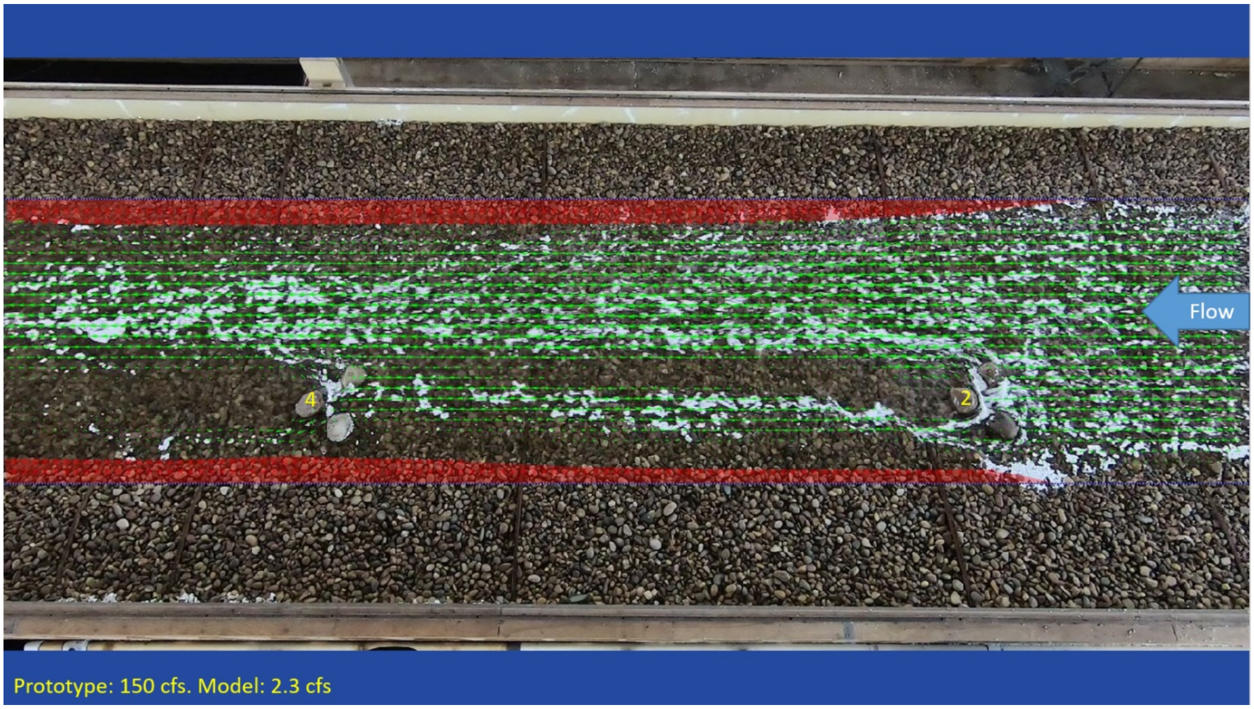

Figure F-118. PIVLab output of velocity vectors at 150 cfs at the small rock downstream “V”, low density configuration through the channel. Rocks are denoted in yellow. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab.

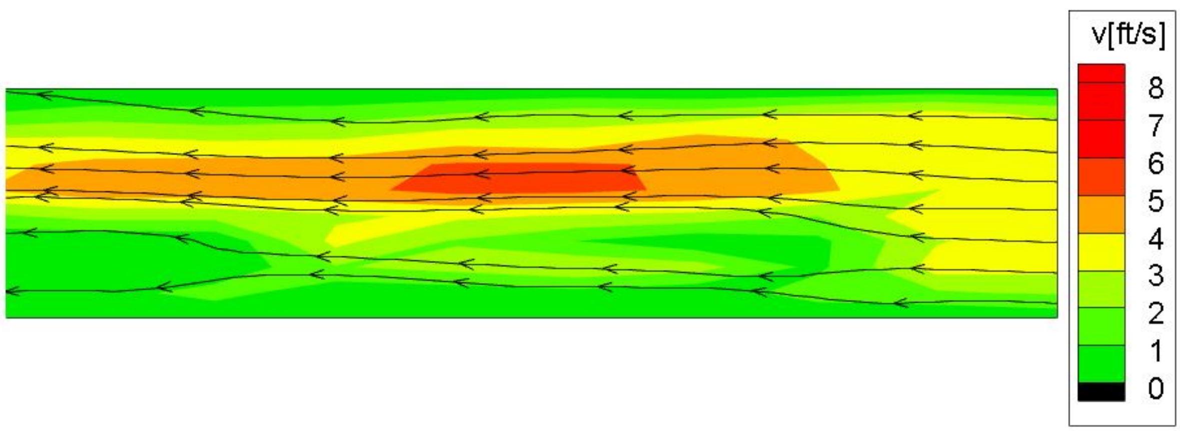

Figure F-119. TecPlot output for velocity at 150 cfs at the small rock downstream “V”, low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

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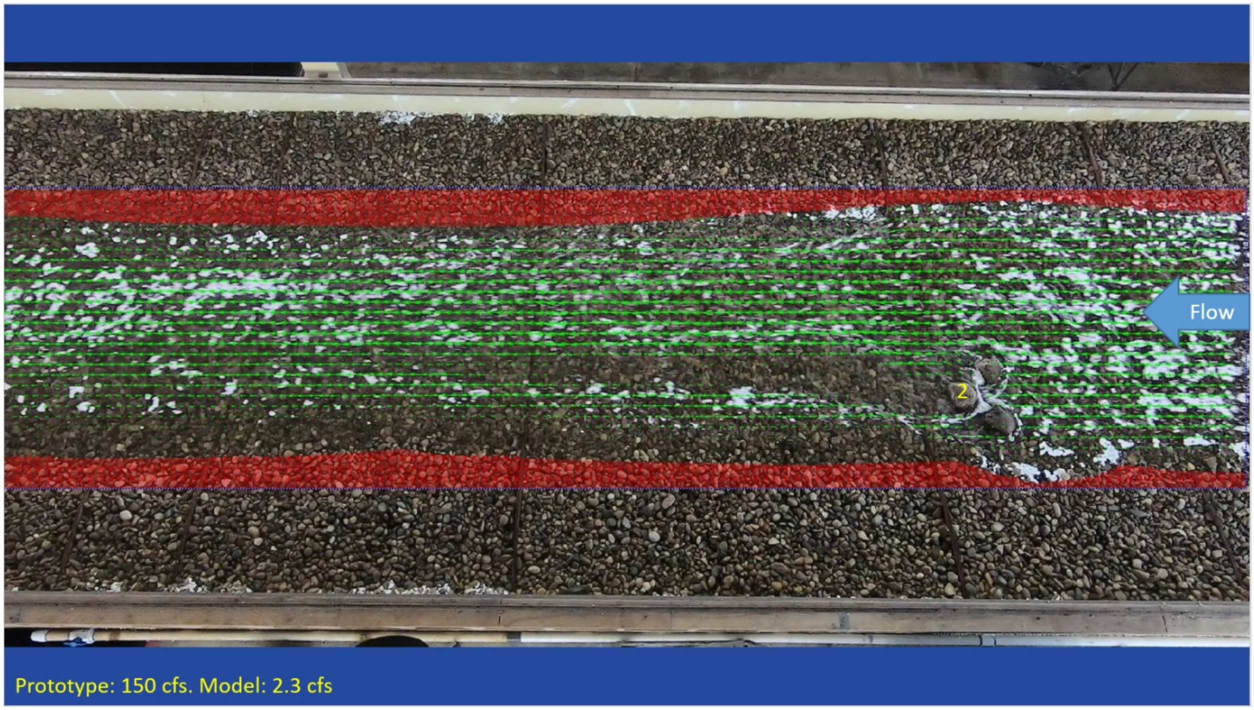

Figure F-120. PIVLab output of velocity vectors at 150 cfs at the small rock downstream "V", very low density configuration through the channel. Rocks are denoted in yellow. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab.

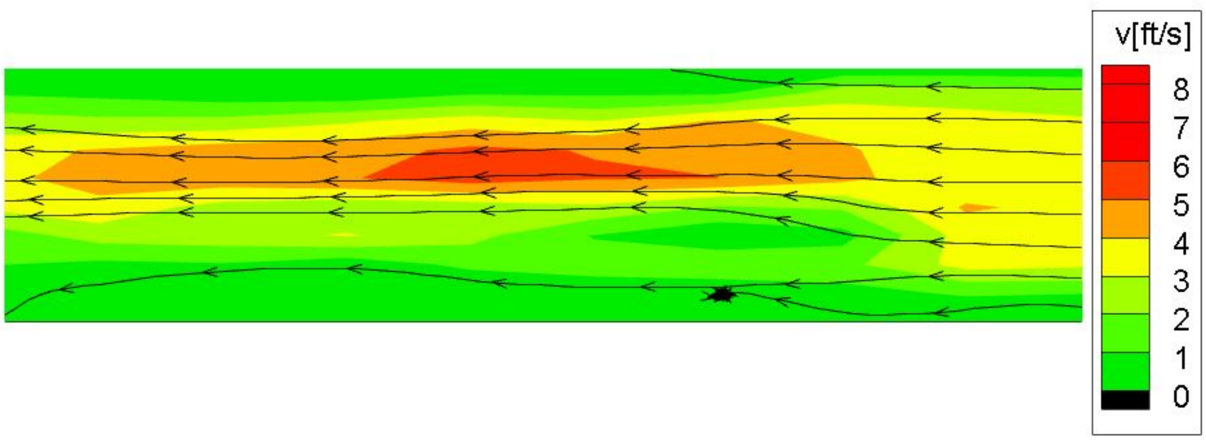

Figure F-121. TecPlot output for velocity at 150 cfs at the small rock downstream "V", very low density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab.

Appendix G: Previous Application of Data

Previously, the data in Appendix E: Velocity Vectors and Magnitude was applied to southern Steelhead in the Los Angeles River. Southern Steelhead require velocities under 3 ft/s for high quality resting areas and under 5 ft/s for moderate resting areas. For a full analysis, please see Holste and Shinbein (2019). When applied to the configurations results could appear as follows:

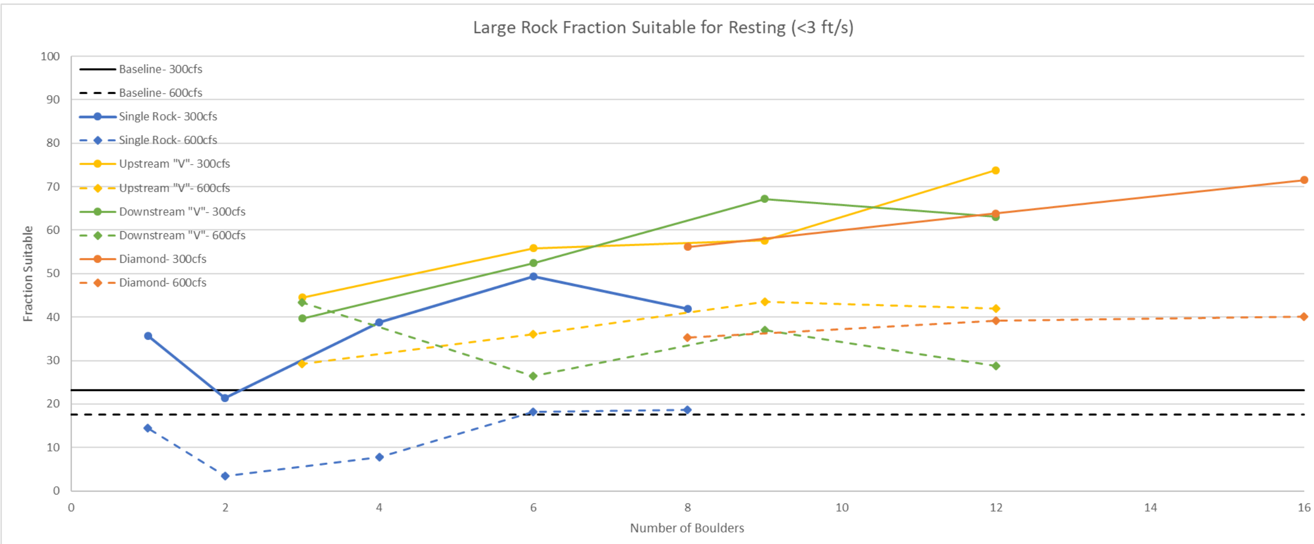

Figure G- 1 Large rock fraction suitable for resting for southern Steelhead (<3 ft/s). Baseline (without any rocks) are shown as horizontal lines in black.

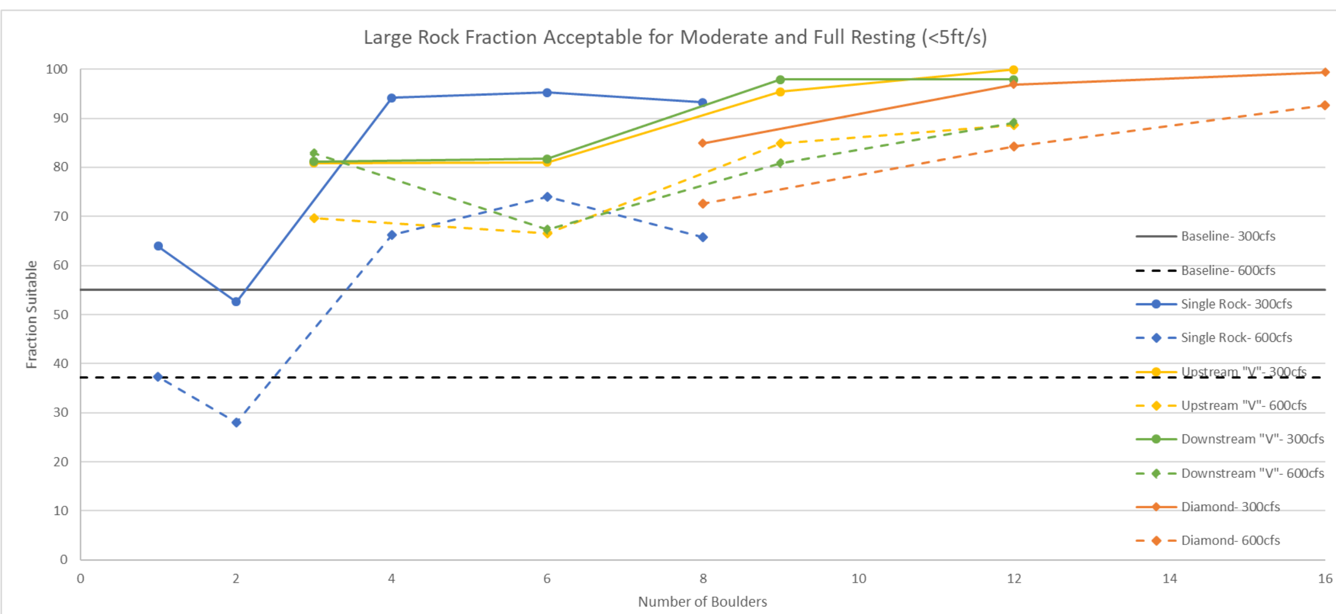

Figure G- 2 Large rock fraction suitable for moderate and full resting for southern Steelhead (<5 ft/s). Baseline (without any rocks) are shown as horizontal lines in black.

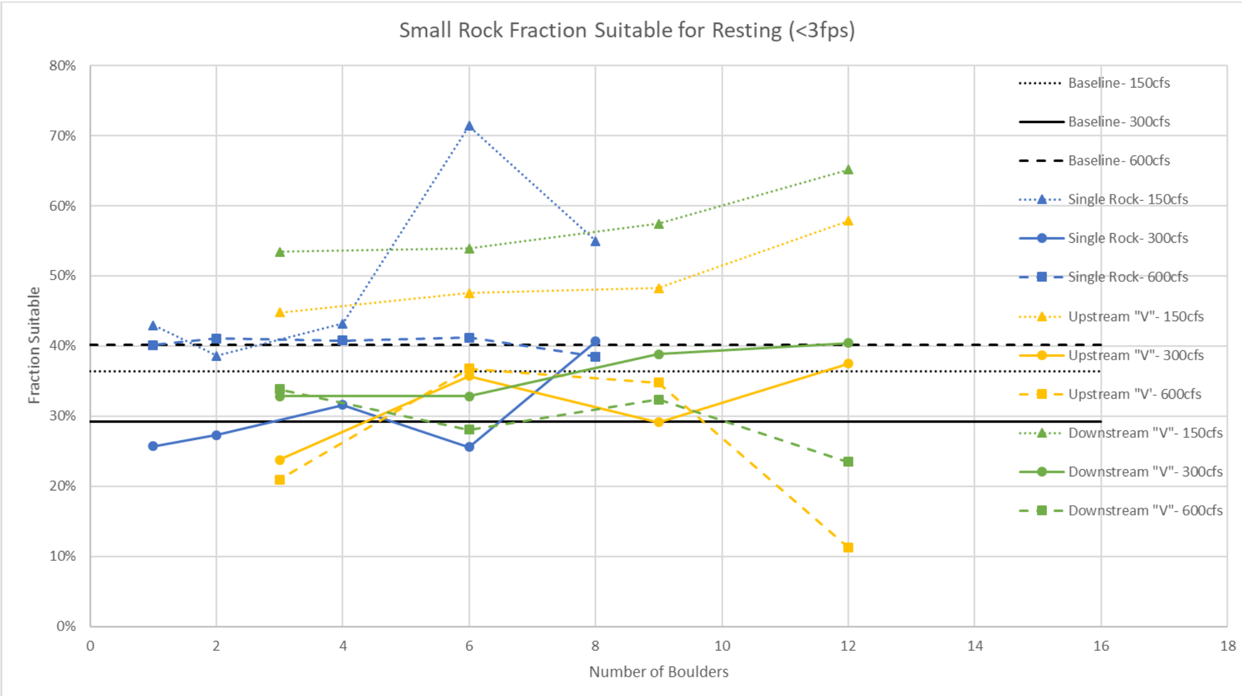

Figure G- 3 Small rock fraction suitable for resting for southern Steelhead (<3 ft/s). Baseline (without any rocks) are shown as horizontal lines in black. Due to post-processing changes to the mask that include shallow sections of flow that were previously omitted, the 600 cfs baseline appears to have a higher fraction suitable to resting than the lower baseline flow rates. This is appearance is resolved once moderate resting zones are considered as well (Figure G-4).

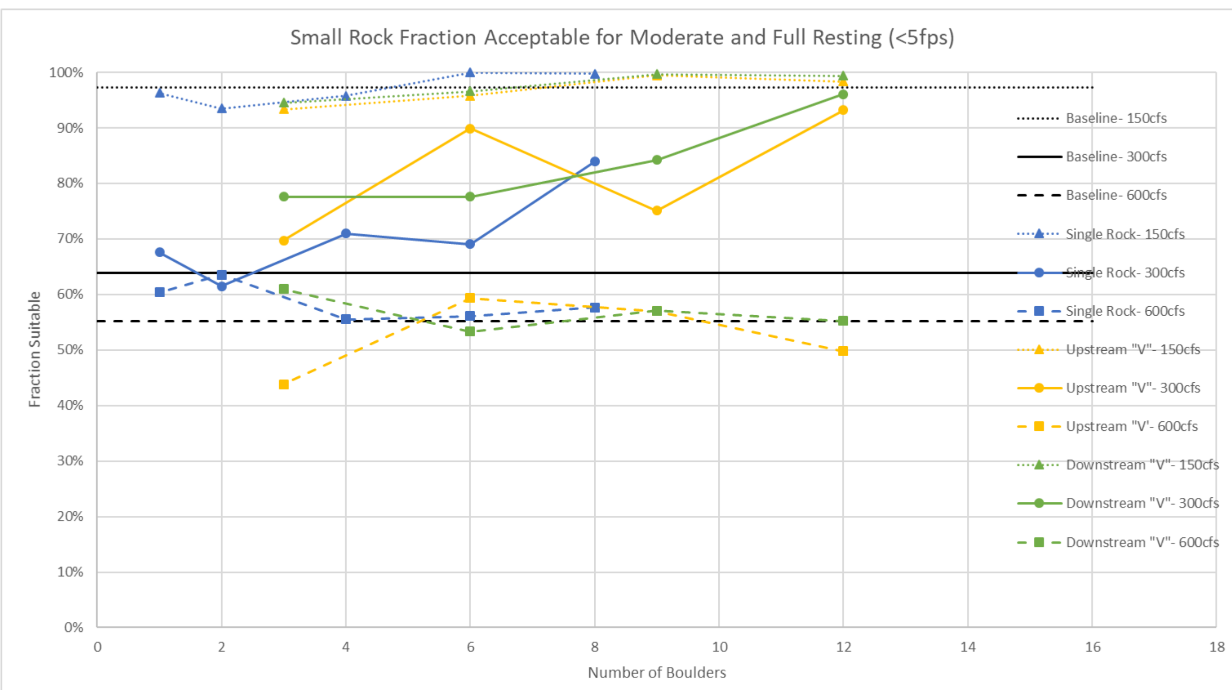

Figure G- 4 Small rock fraction suitable for moderate and full resting for southern Steelhead (<5 ft/s). Baseline (without any rocks) are shown as horizontal lines in black.