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Testing of Boulder Clusters from Model to Field

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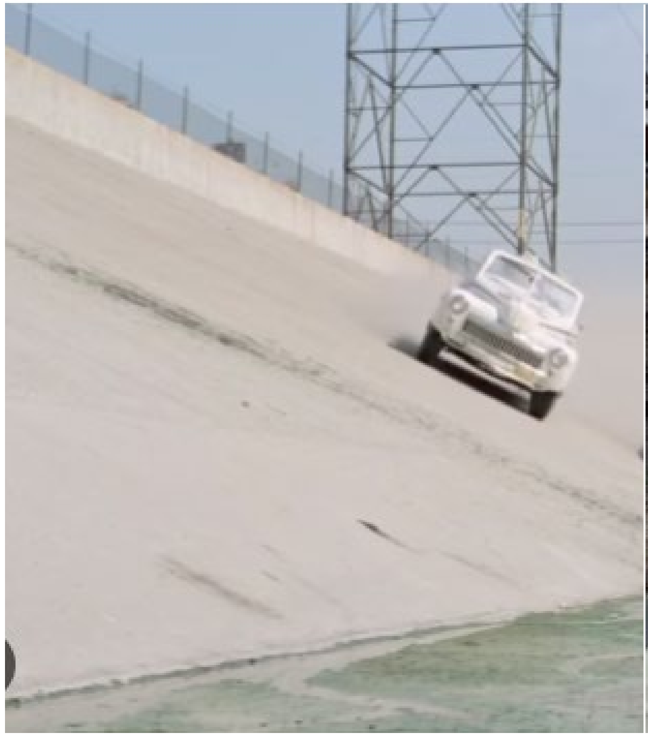
Melissa Shinbein is a hydraulic engineer with the Bureau of Reclamation and has worked on physical modeling and hydraulic analysis in dam safety, fish passage, and river restoration. Previously, she worked for the Pennsylvania Department of Environmental Protection as a regulator of stormwater management and waterways. She is a registered professional engineer with a Master of Engineering and a B.S. in Civil Engineering from Cornell University.

Outline (6 years of work in 1 presentation)

1. Original Project – lab and numerical modeling
2. Spinoff Project – generalization of lab data
3. Field Project – collecting data around boulder clusters at Wenatchee and Entiat

Anyone ever see Grease?



Purpose

- Create a physical hydraulic model with a roughened low flow channel
- Collect more detailed hydraulic data around various boulder cluster configurations than 2-D modeling could provide
- The purpose was to identify the most effective boulder cluster configurations to create low-velocity resting habitat for migrating adult steelhead

Hydraulic Investigations and Laboratory Services

- Bureau of Reclamation-Denver Technical Service Center
- Utilizes venturi system with 12” horizontal pumps
- 240,000 gal reservoir
- Venturi meters calibrated using 44,000 pound volumetric weigh tank
- Accuracy of ±0.25%.

Physical Hydraulic Model

- Set up: template system

- Distorted Vertical Scale
  - Distortion Ratio of 2
  - Allows for increased water depth in model
  - Beneficial for river models

- Model Dimensions
  - Avg Slope: 0.0089 ft/ft

Configurations and Density

- Baseline: roughened channel with scaled gravel
- Four configurations; 4-5 densities
- Three flow rates: 150, 300, and 600 cfs (2.3, 4.7, 9.4 model cfs)
- Two rock sizes: “small” and “large”

Testing Techniques

- Large Scale Particle Image Velocimetry (LSPIV)
  - Surface velocities
  - Streamlines around the rocks
- Acoustic Doppler Velocimeter (ADV)
  - Single point at 60% of water depth
  - Around clusters including upstream and downstream

Velocity Criteria

<3 ft/s: High Quality Resting Area

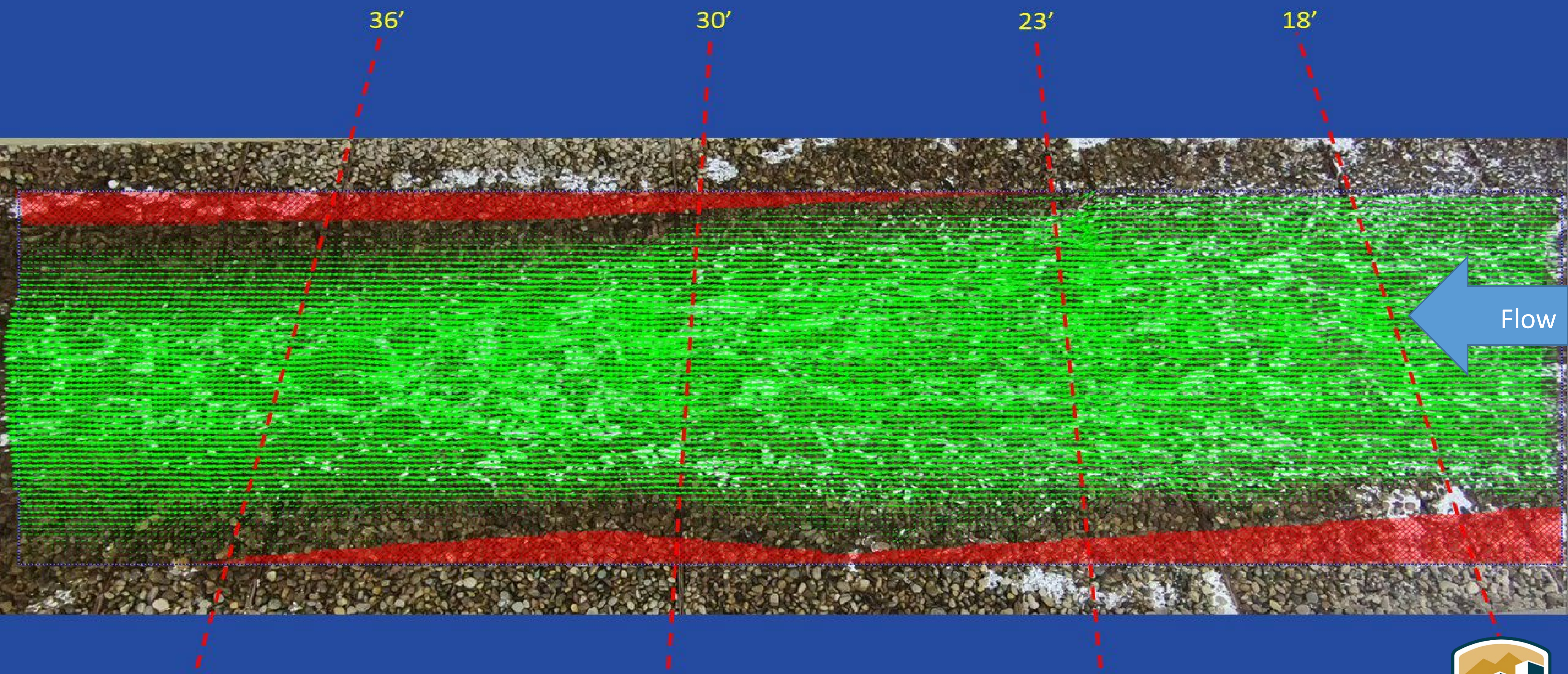
3-5 ft/s: Low Quality Resting

>5 ft/s: Unsuitable for Resting

Depths >1ft

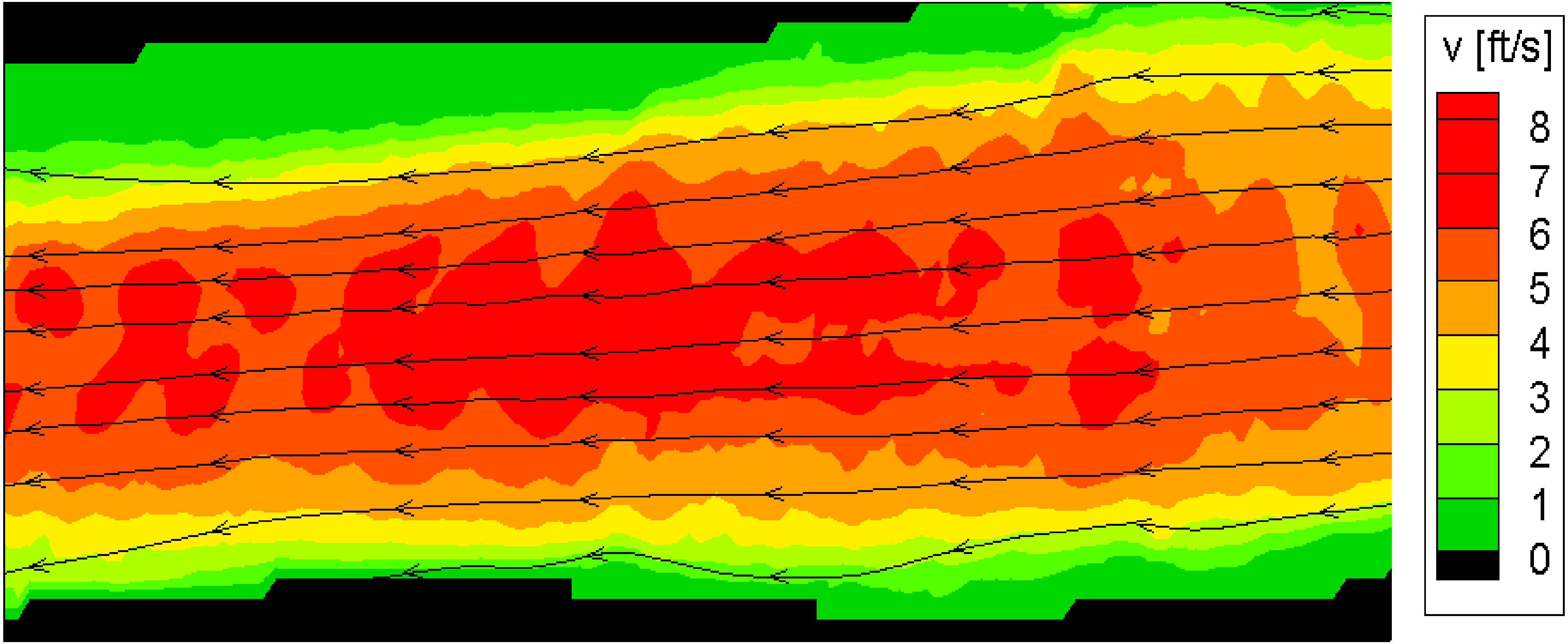
Bell, 1991.

LSPIV Results- 300 cfs Baseline

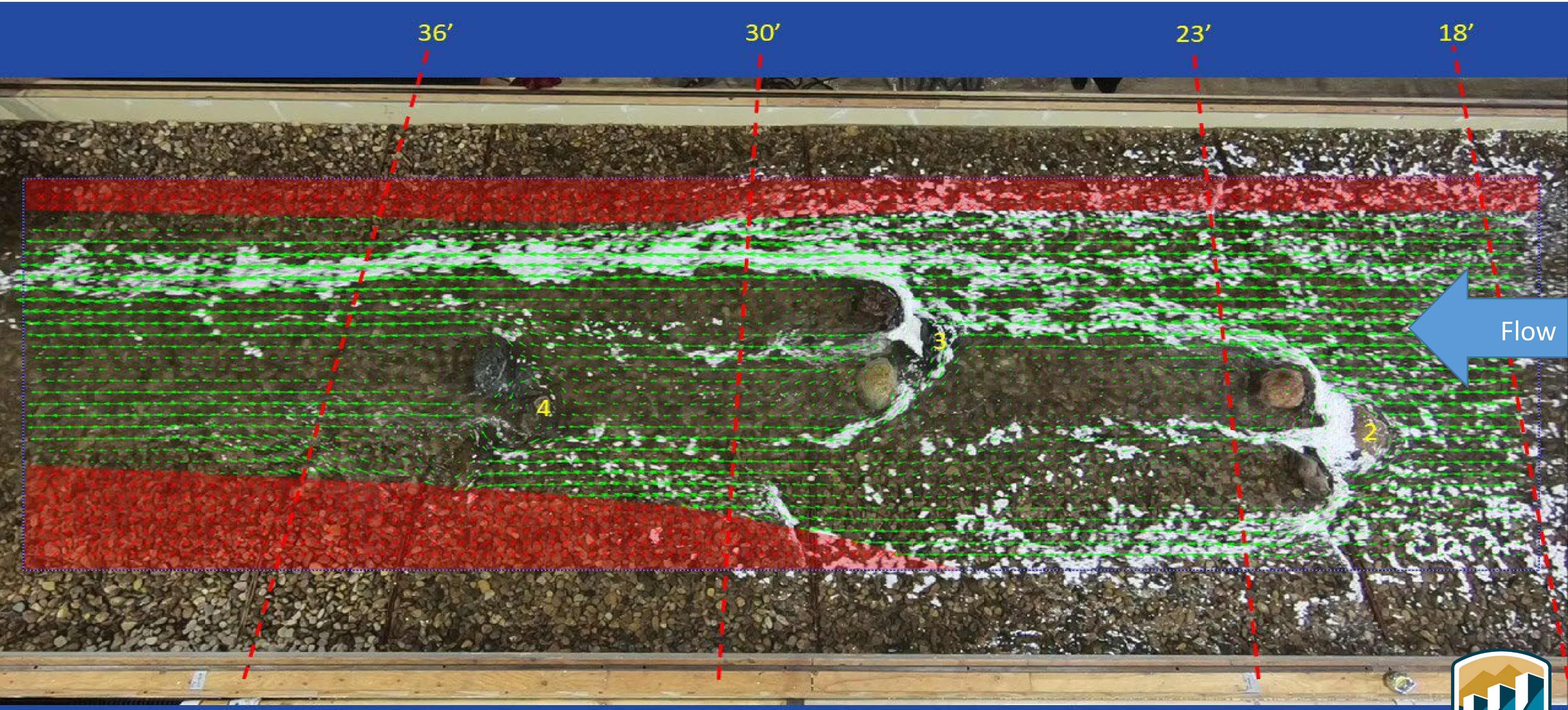


Prototype: 300 cfs. Model: 4.7 cfs

TecPlot Results: 300 cfs Baseline



300 cfs Large Rock Upstream “V” Medium Density



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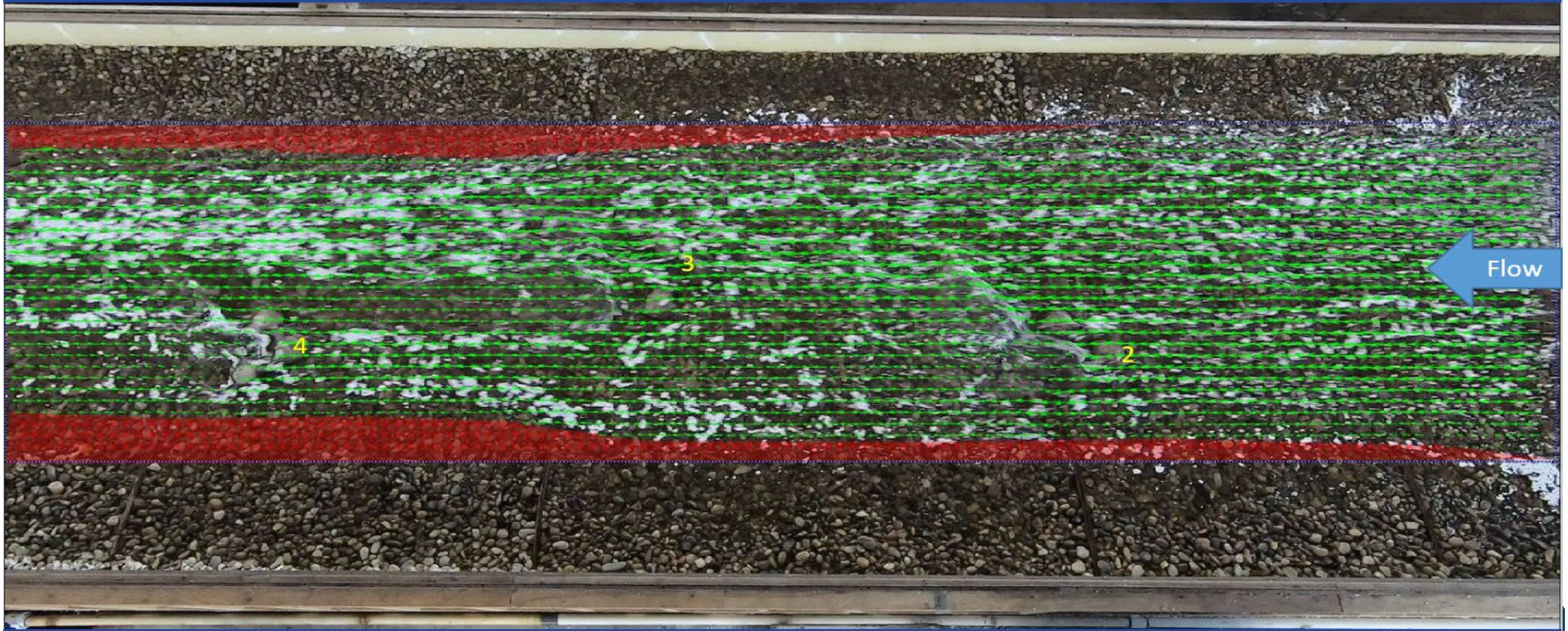

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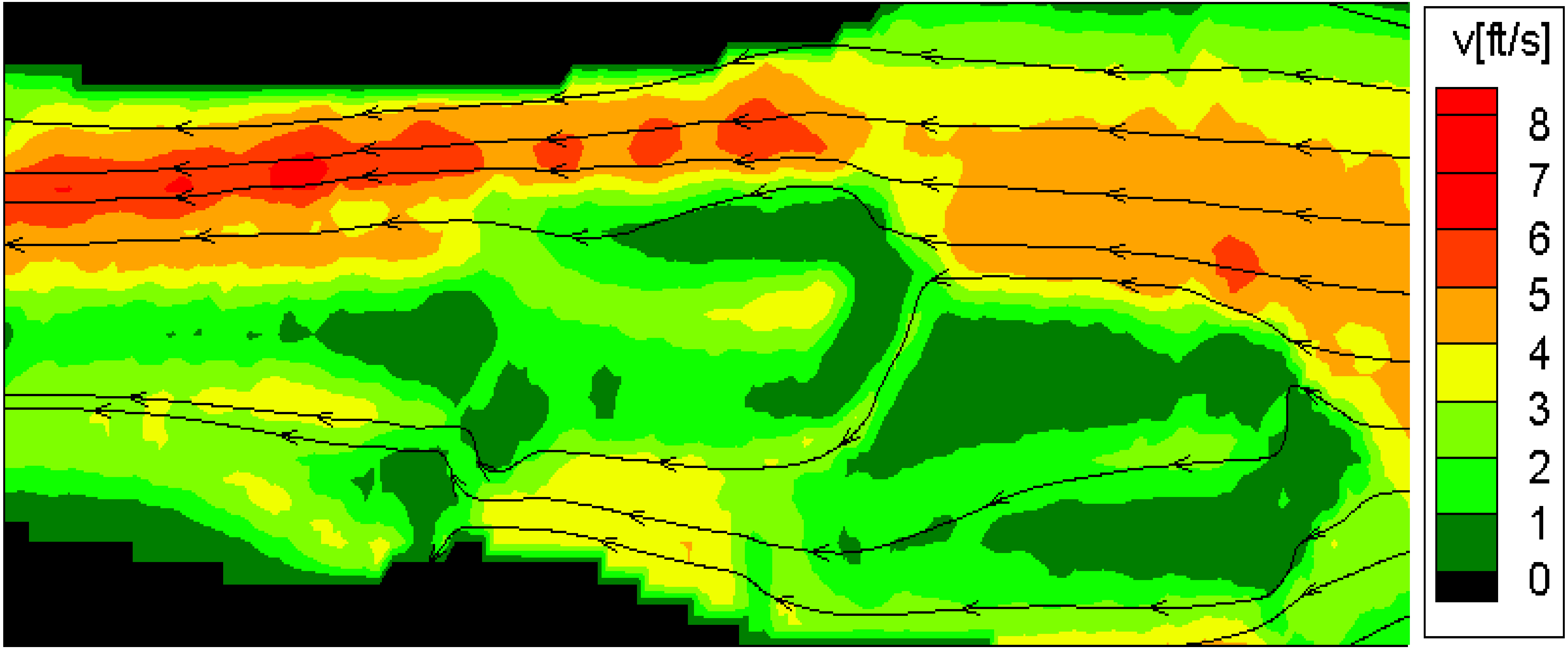

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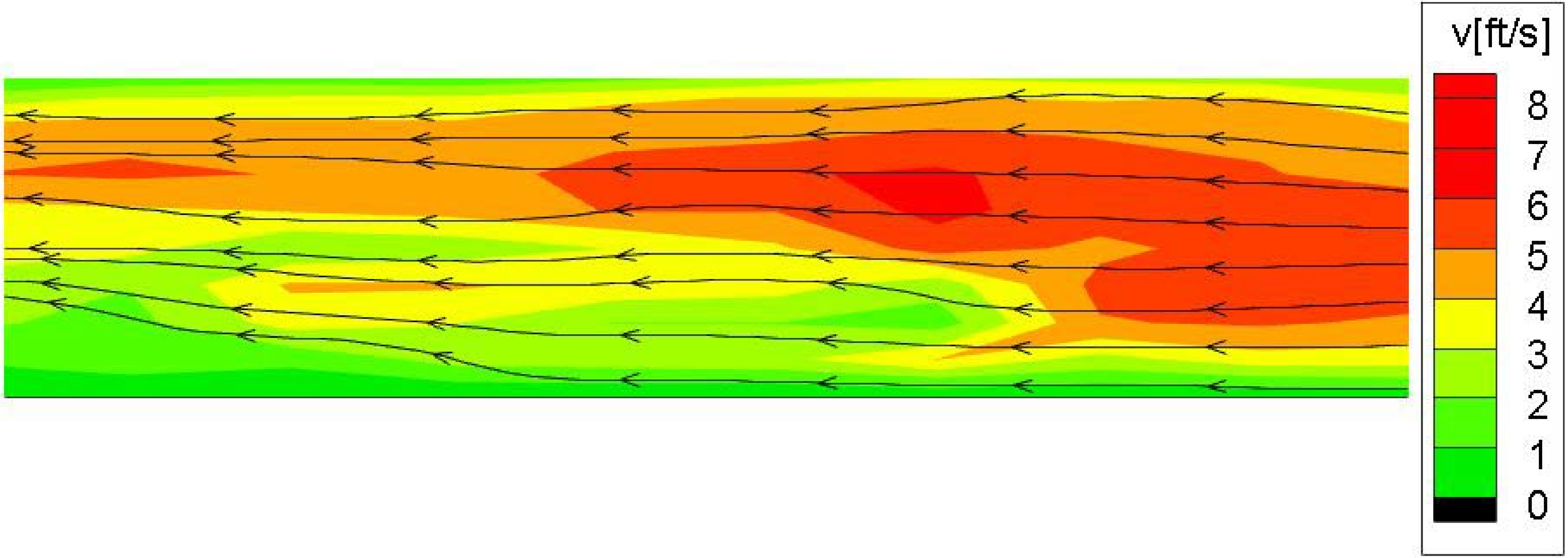
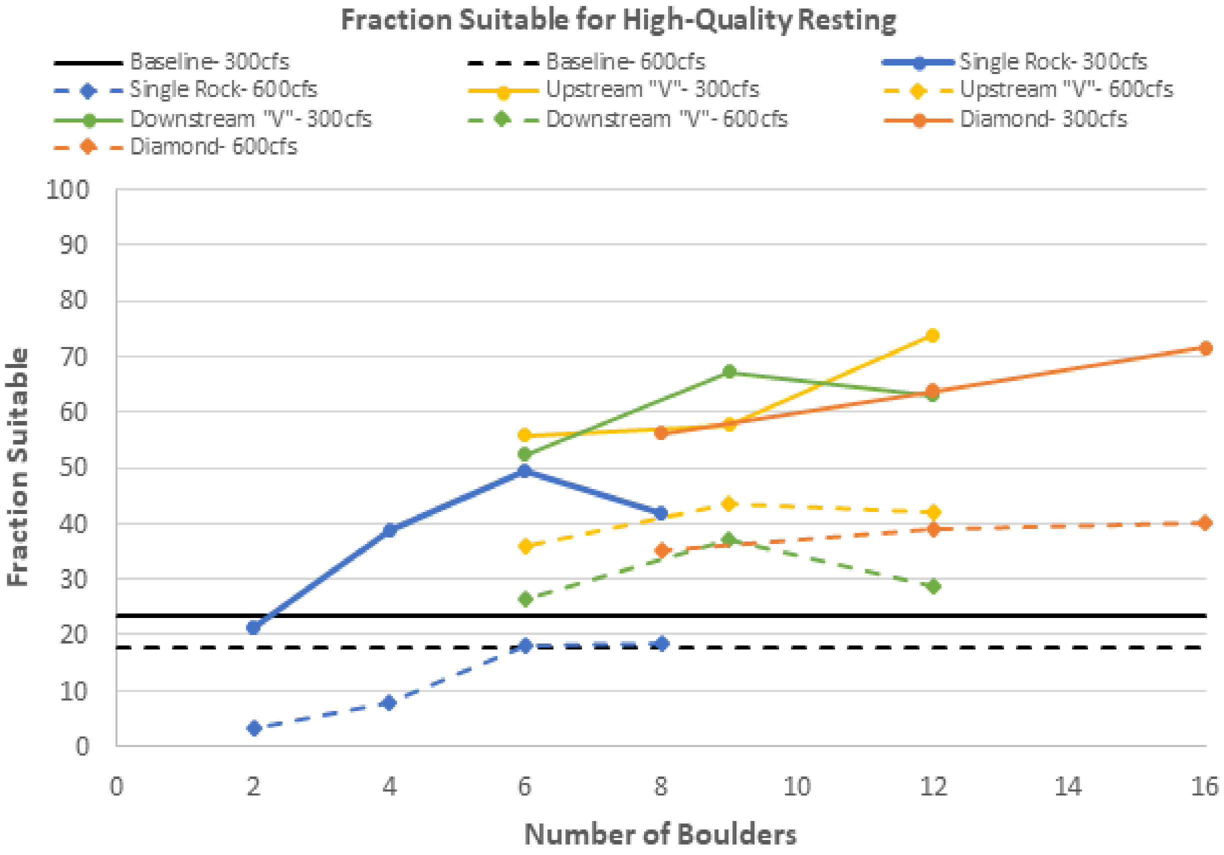
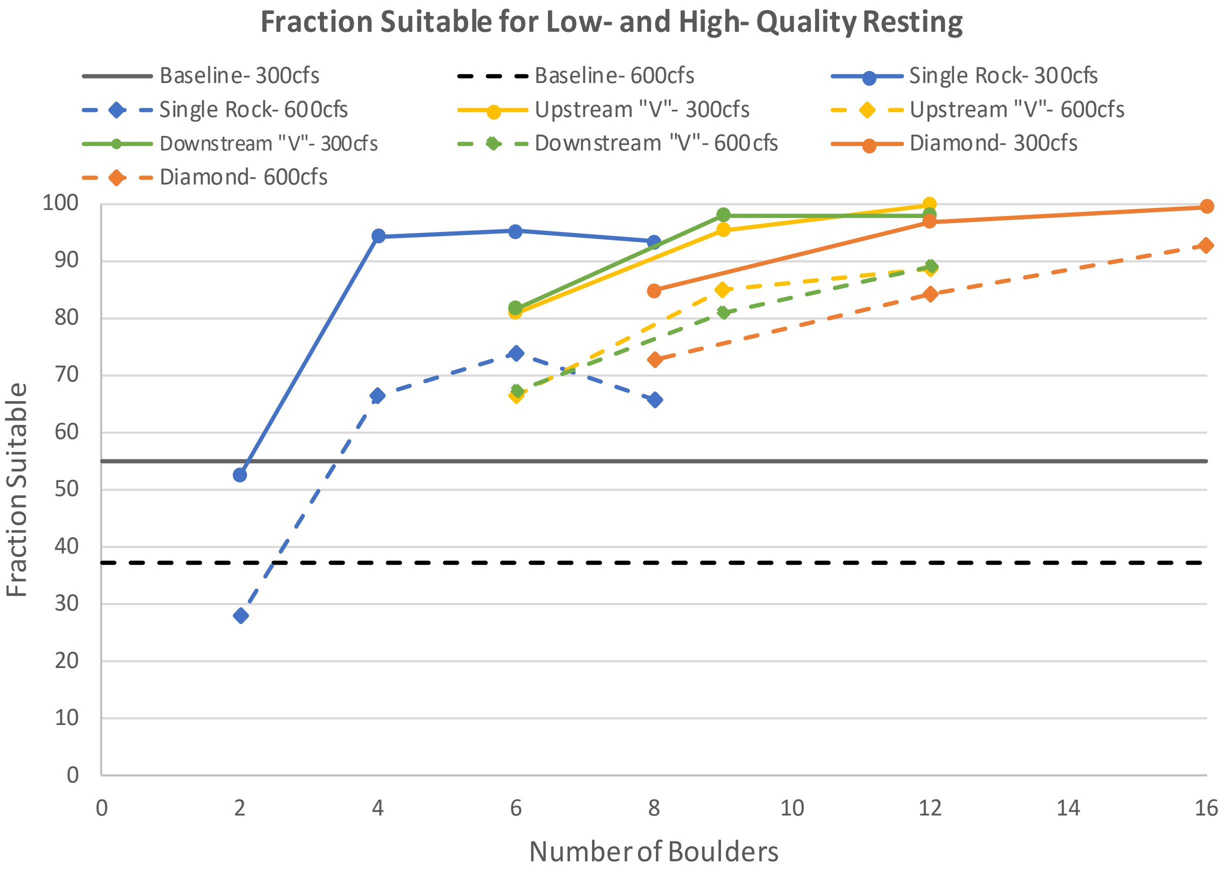
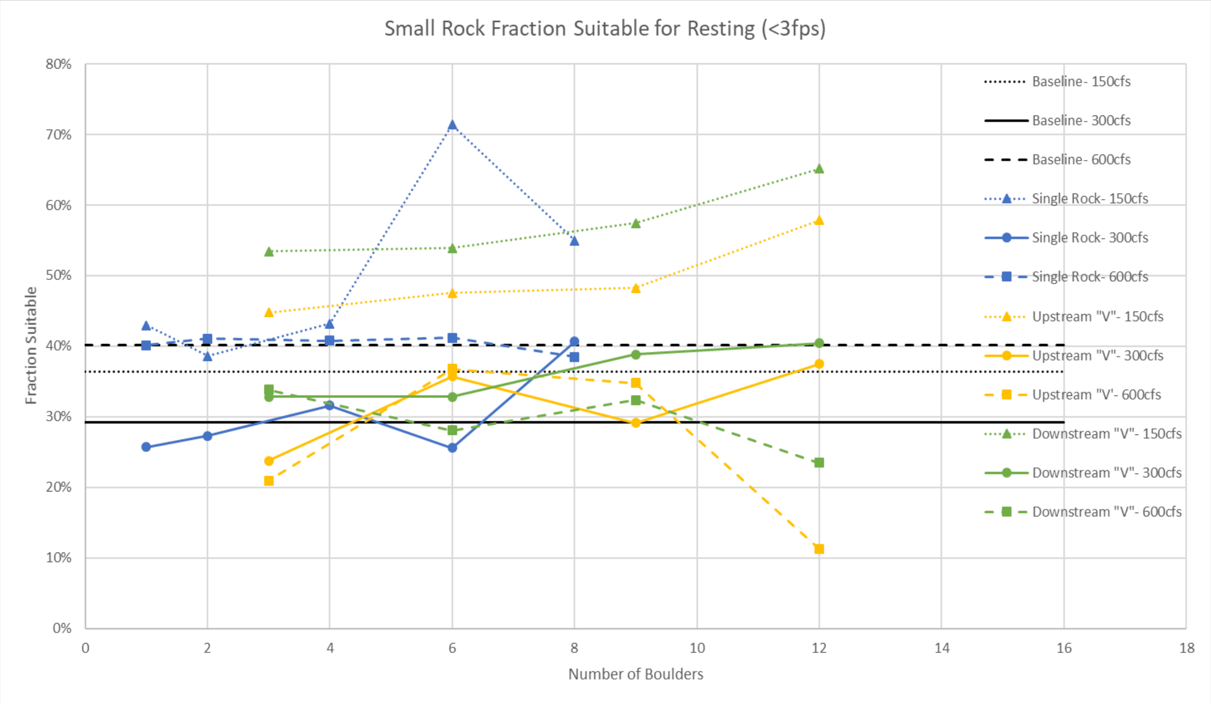


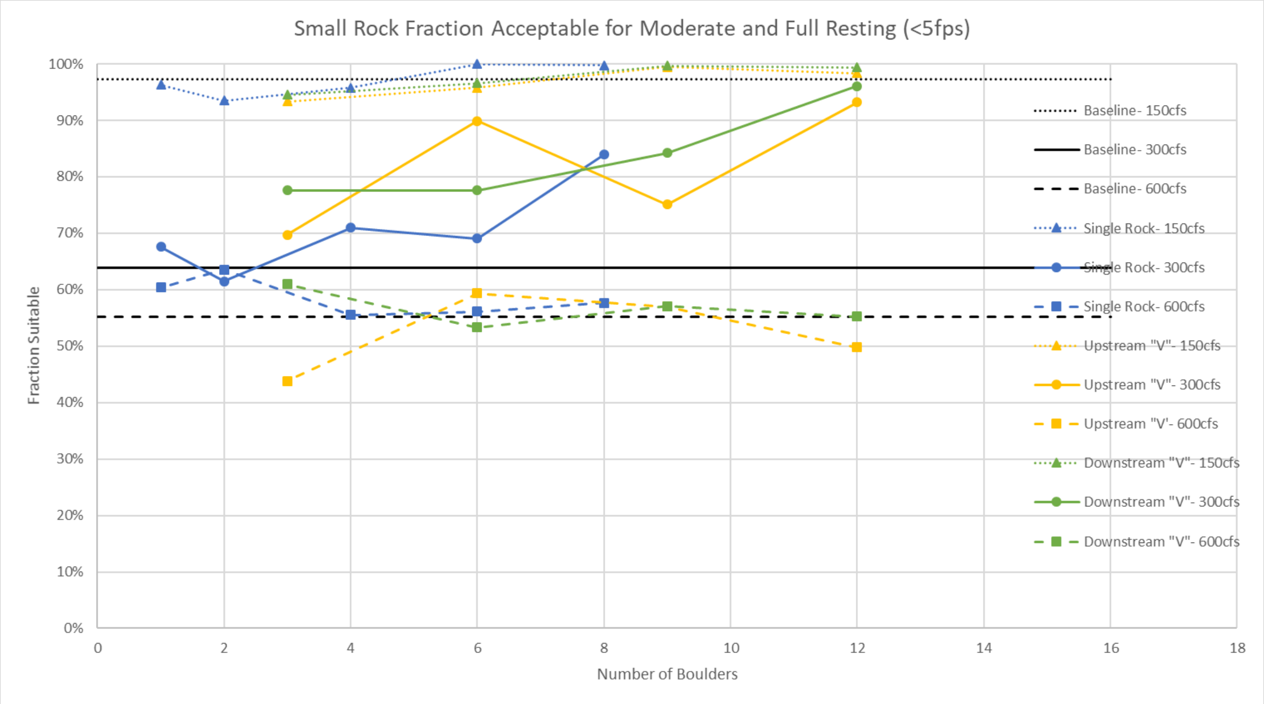
Overall Results- Large Rock





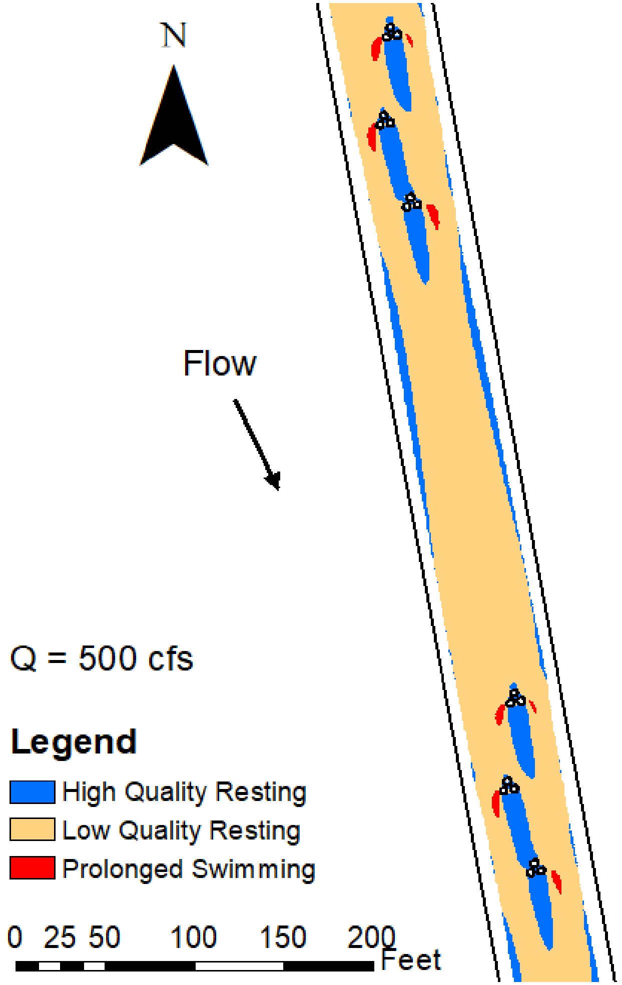
Overall Results- Small Rock





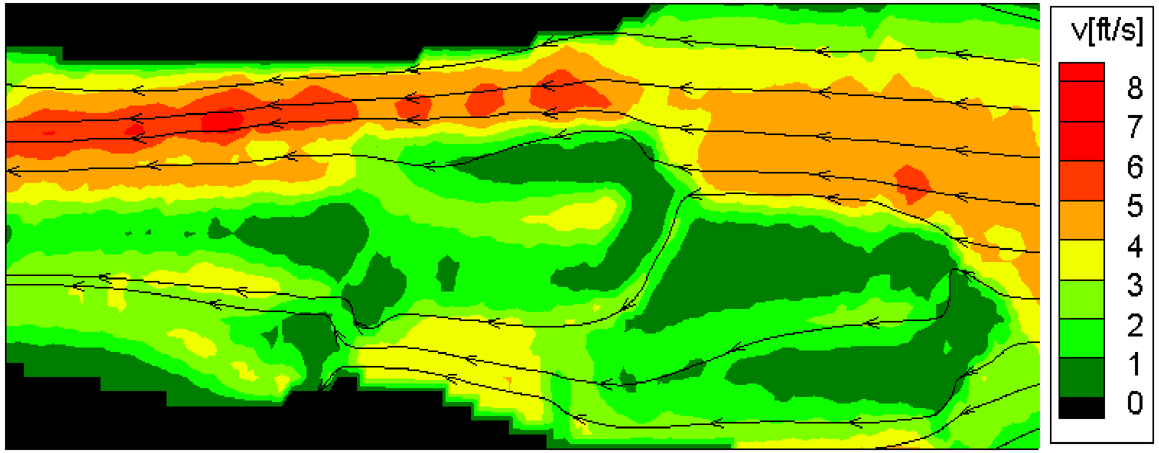
Numerical Modeling

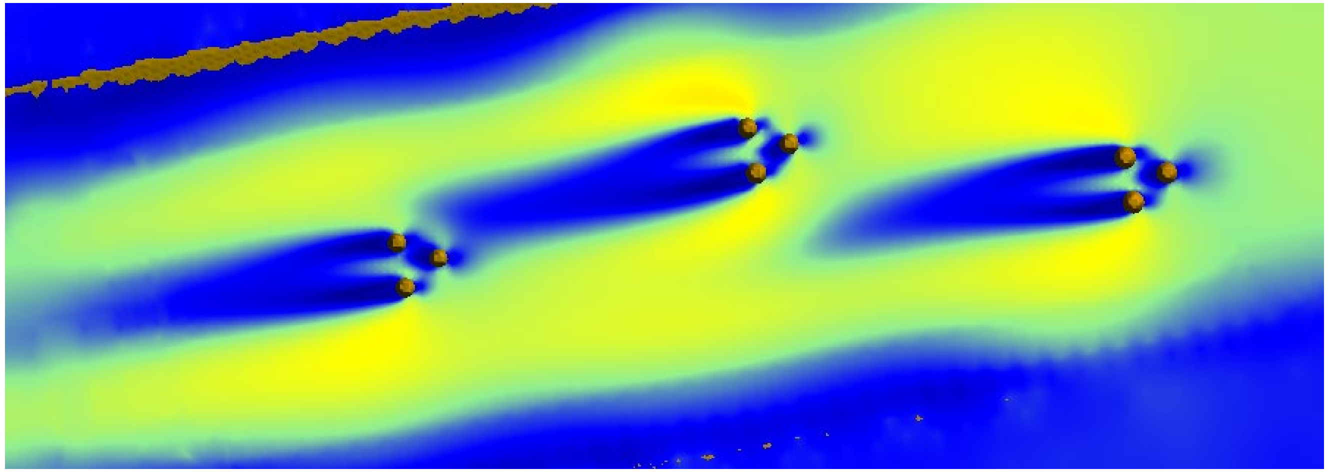
- Nathan Holste
- HEC-RAS 2D for the upstream V configuration
- SRH-2D for a combination of boulder types
- Mesh with 1-ft cell sizes for topography near the boulders; 2-ft cells further from the boulders; 4-ft cells within the low-flow channel in regions not influenced by the boulders
- Flows from 10 – 4,000 cfs



Numerical Modeling Conclusions

- 2D numerical model results indicate that boulders installed within the low-flow channel of the LA River provide suitable fish passage up to about the 1% exceedance mean daily flow





Conclusions- Part 1

- Single rock: where low-quality resting deemed suitable
- Downstream “V”: where sufficient freeboard exists for backwater
- Upstream “V”: provides most resting habitat at high flows
- Diamond “V”: performed similarly to Upstream “V” but requires an additional rock

Okay but that's only for one system…

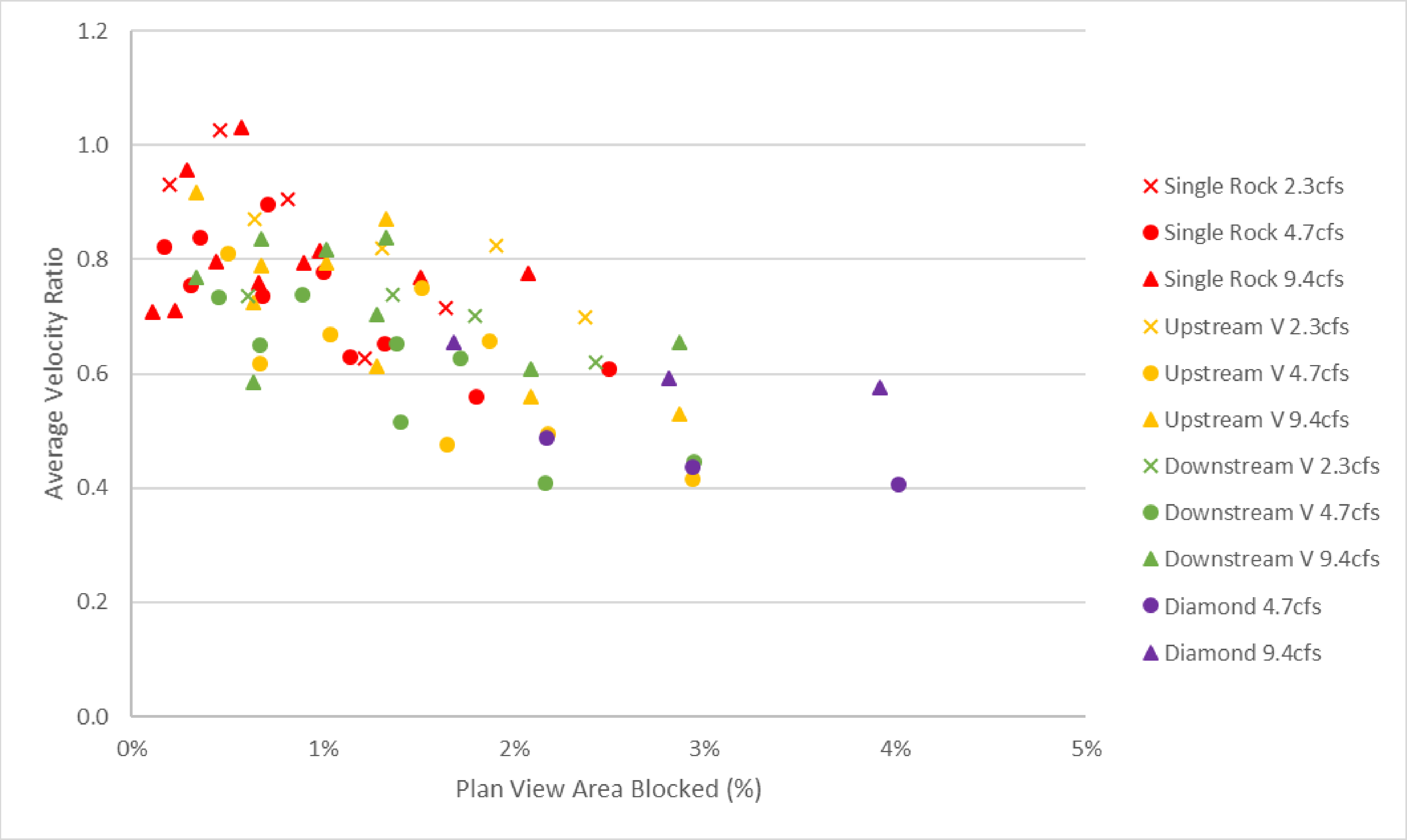
- Project #2
- 2020 Study from the California-Great Basin Area Office to generalize data
- Addition of the small rocks in physical model testing to correct for boulder sizes

Analysis (it's a lot)

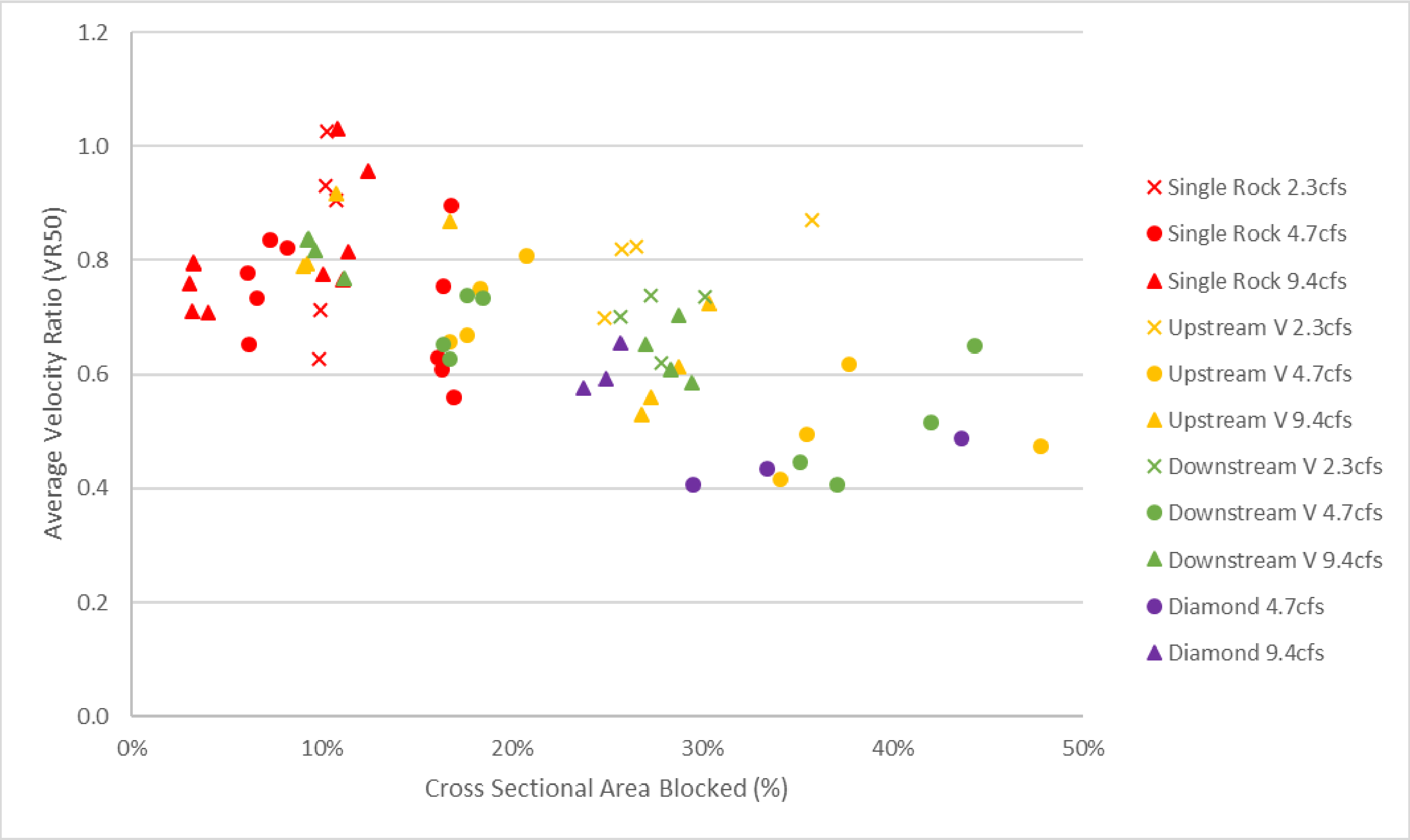
- Boulder Properties
- Flow Properties
- Dimensionless Analysis
- Velocity Analysis

Velocity Ratio over % Plan View Area

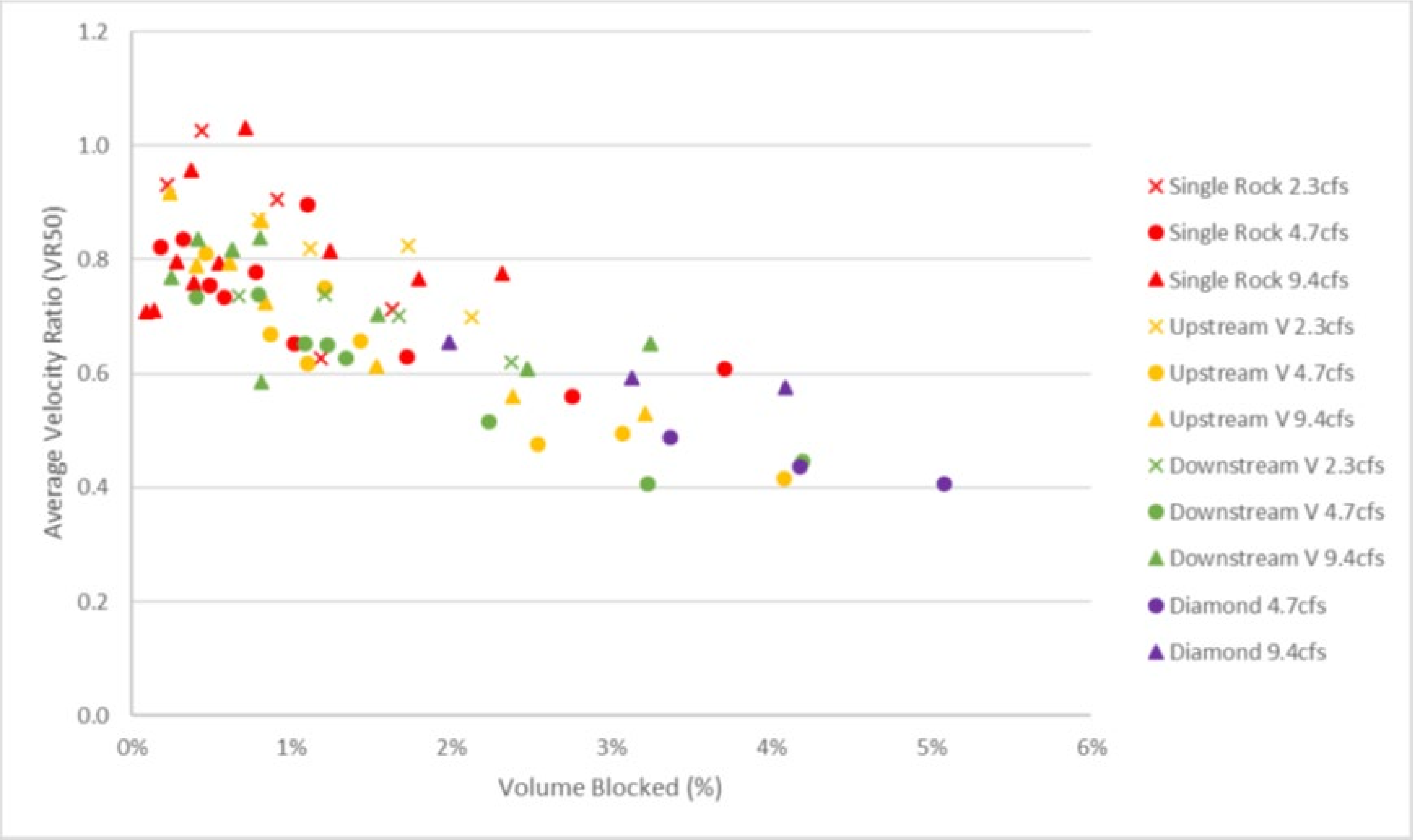
$$VR = \frac{v_{AvgTest}}{v_{AvgBaseline}}$$



Velocity Ratio over % Cross Sectional Area



Dimensionless Analysis- % Volume Blocked

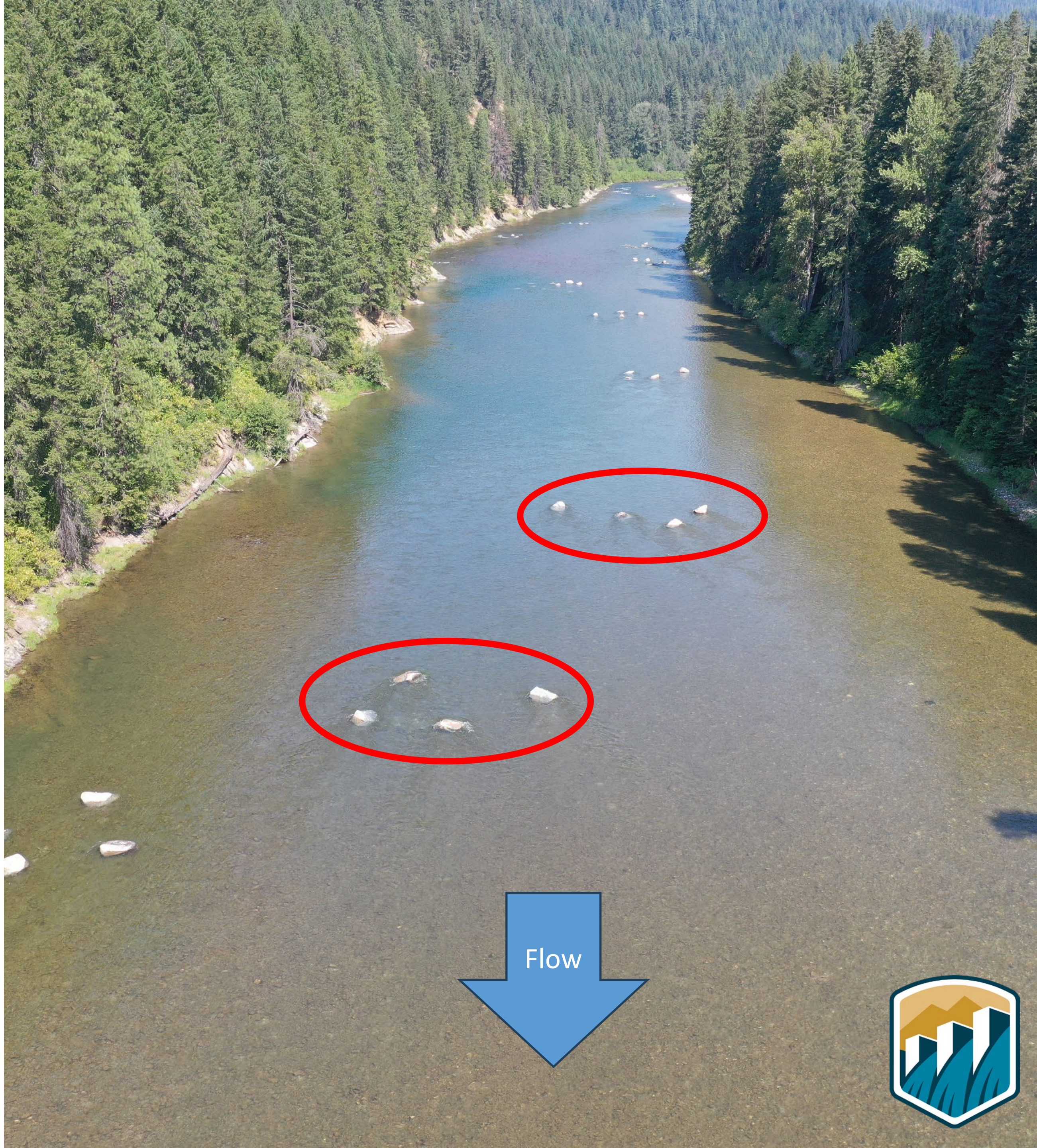


Conclusions- Part 2

- Percent plan view area blocked:
  - Upstream and Downstream V configurations perform best relative to boulder density
  - 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
  - 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.
  - This indicates there may be an optimal value around 2 to 3 percent blocked.
- Percent cross-sectional area blocked:
  - 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.
  - 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%.
- Volume blocked:
  - Once 2 to 4% of the volume was blocked, all ratios fell below 0.65 for all configurations.
  - Need to test higher percentage of volume blocked

So, how does it compare to reality?

- Site visit in September 2024 to Wenatchee and Entiat
- Goal to see if boulder clusters and models agree
- LSPIV and ADV Data

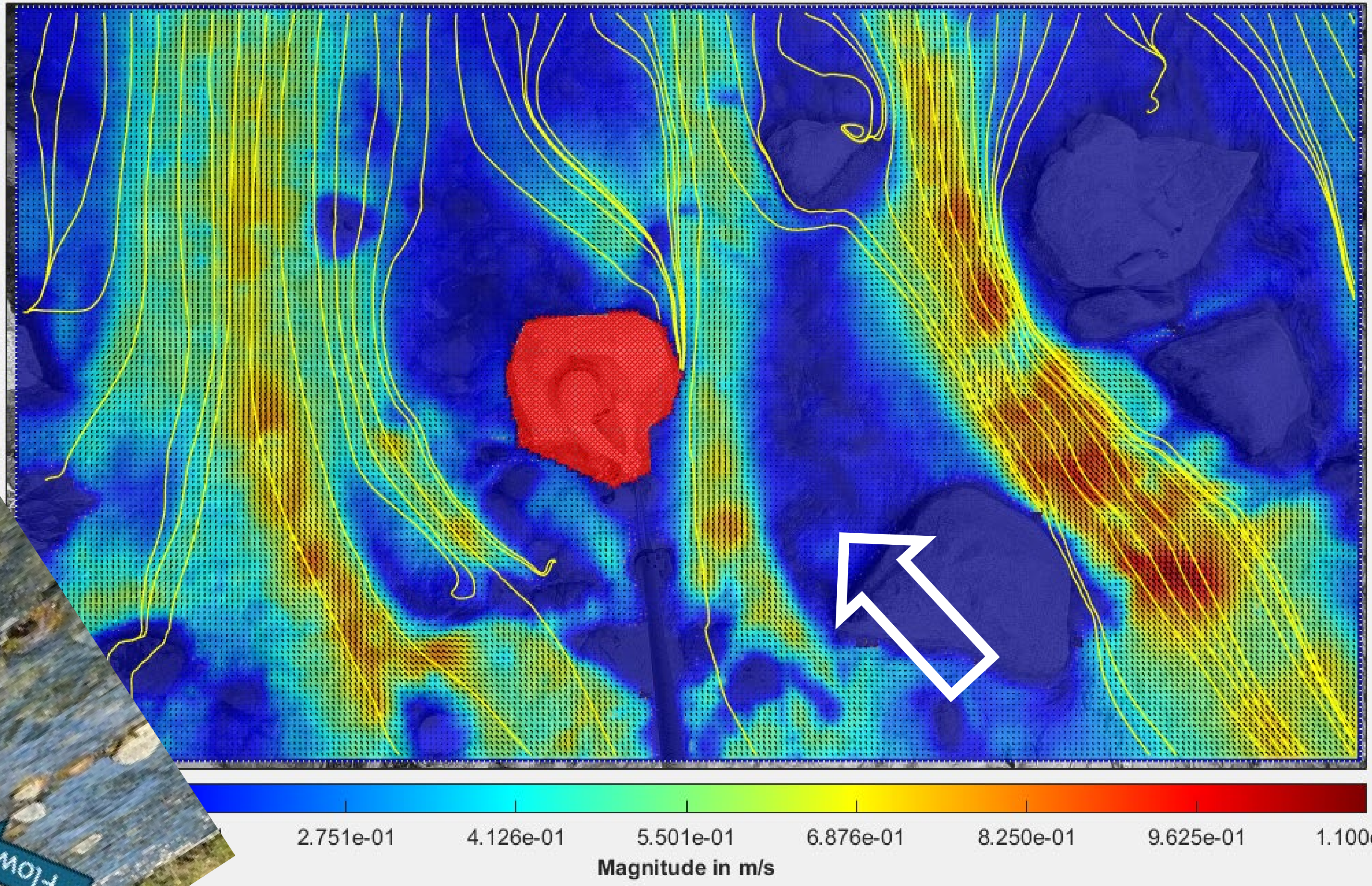


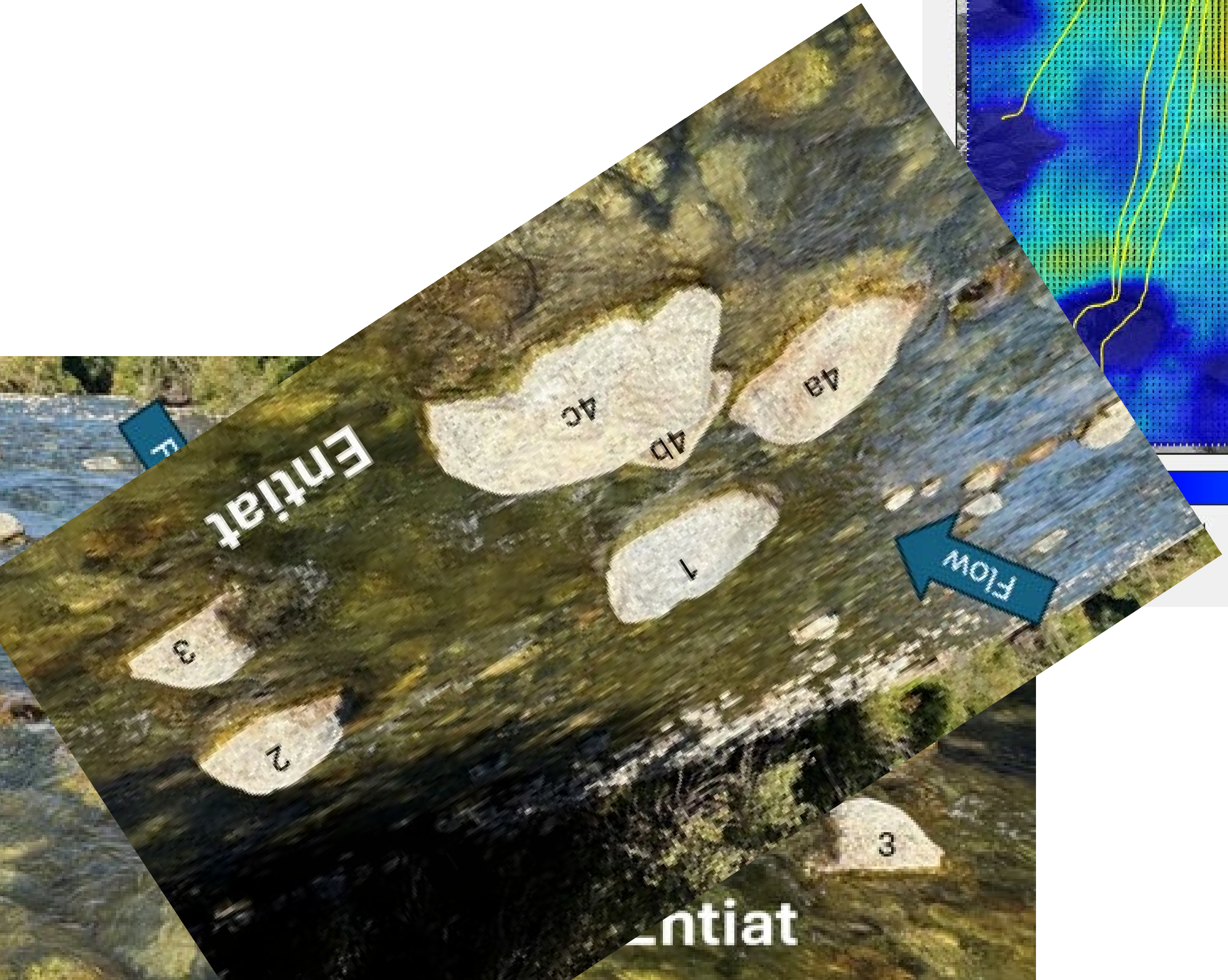
Entiat – ADV Data

- USGS Stream Gauge: 75 cfs (our measurement was 79 cfs)
- Boulder clusters were much closer together, so could not assess how far of an impact downstream to velocity
  - Upstream of clusters: 1 ft/s average velocity
  - Within the boulder field: 0.83 ft/s
- These boulders were interacting with each other within a cluster!
  - Recirculation within the cluster with velocities ranging from -.2 ft/s to 0.1 ft/s

Entiat – LSPIV

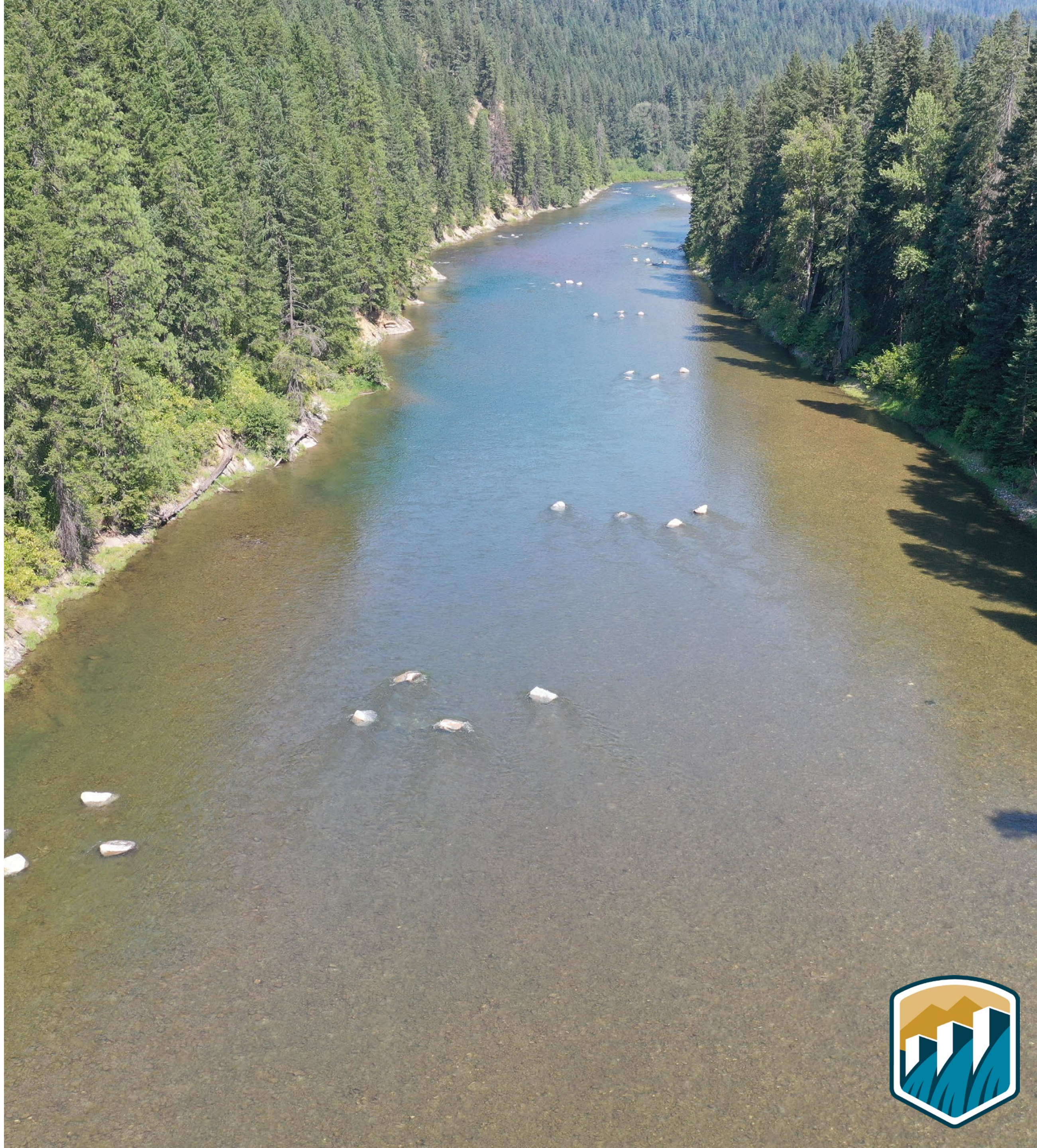
Leftmost rock (Rock #2)



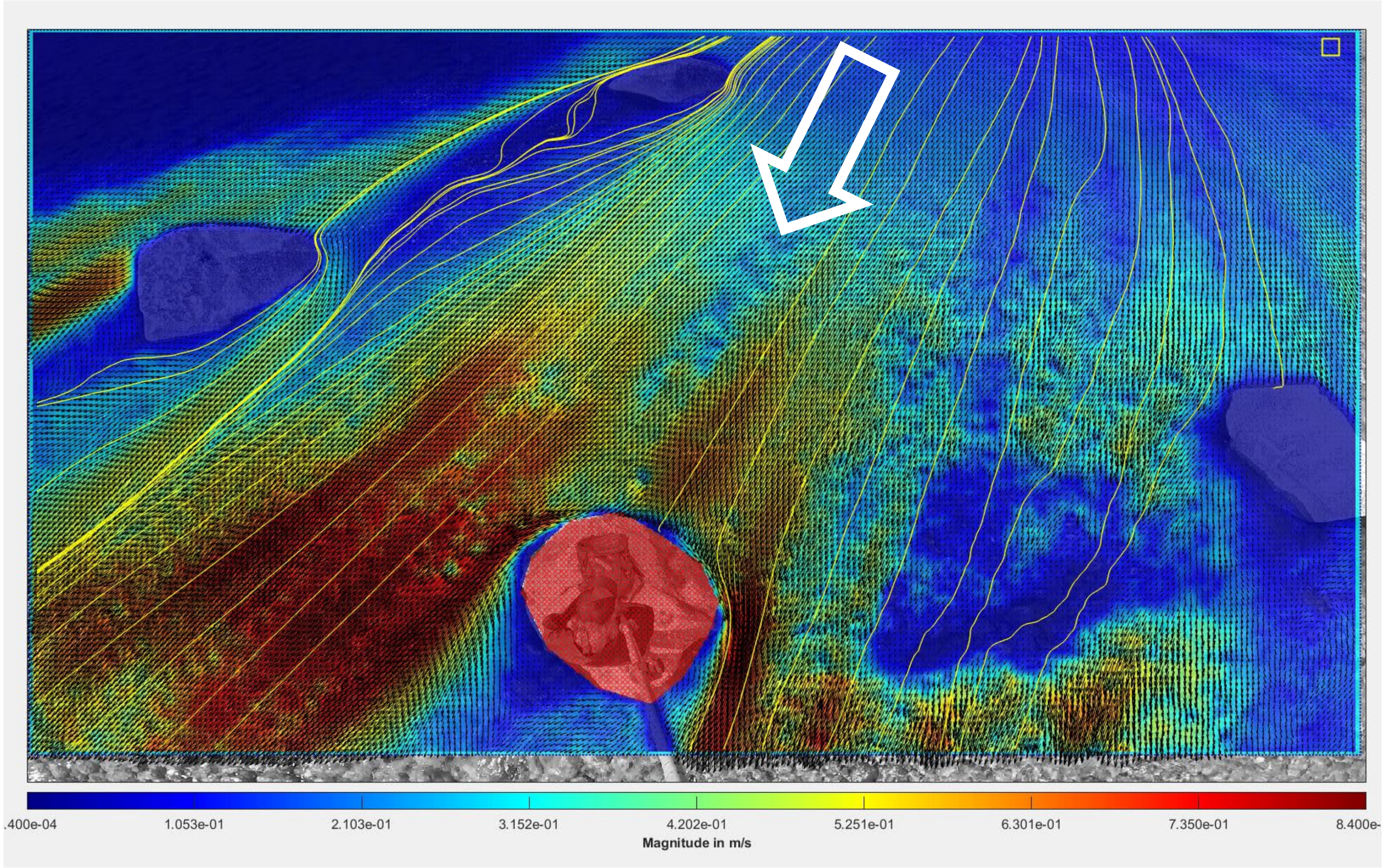


Wenatchee – ADV Data

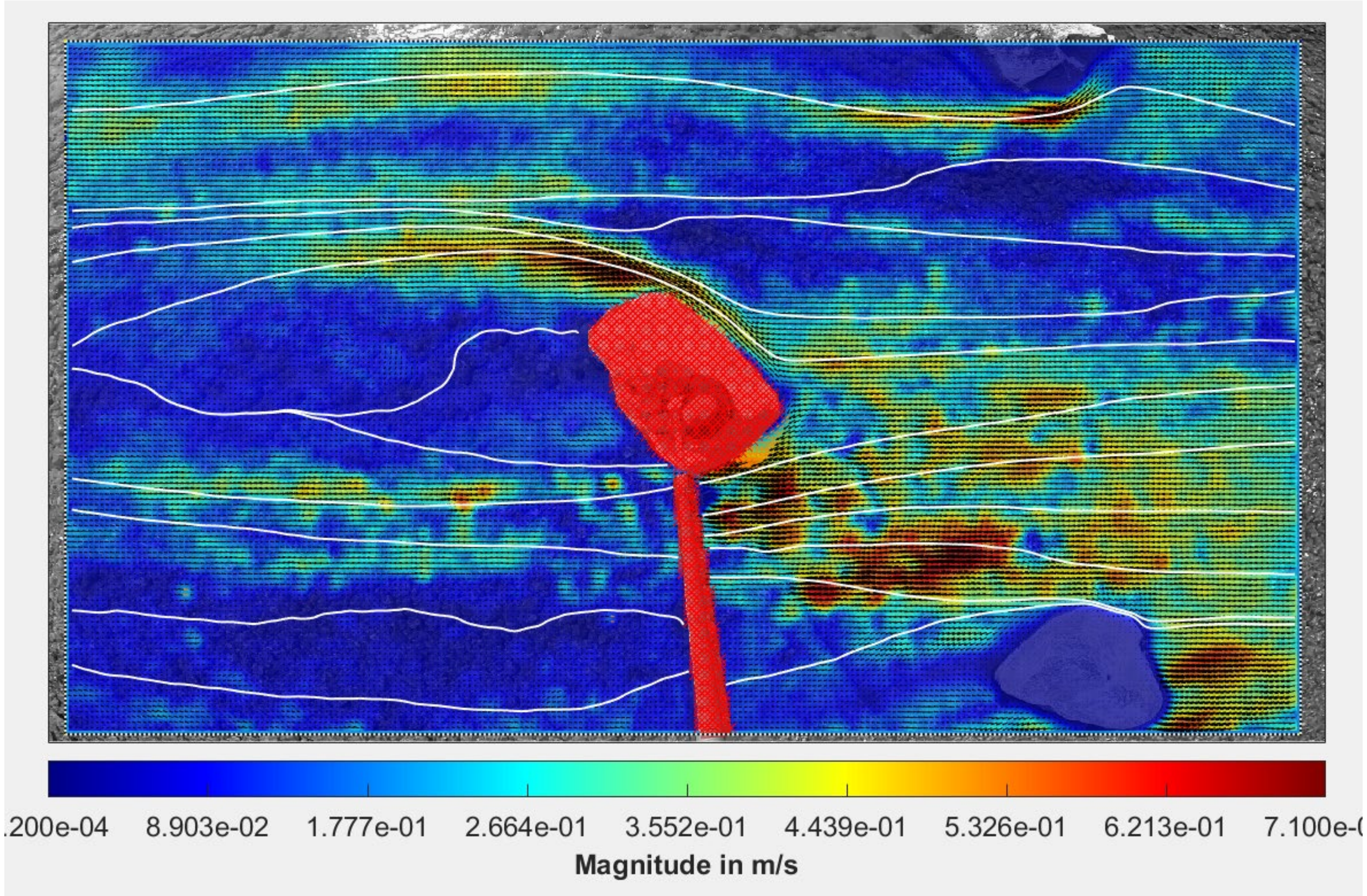
- USGS Stream Gauge Data: about 360 cfs (our measurement about 390 cfs)
- Velocity Upstream of Cluster: Ranging from 1-2 ft/s
- Velocity Downstream of Cluster:
  - Up V: 1.2 ft/s (lowest points within 6ft of cluster at 0.4 ft/s)
  - Diamond: 0.9 ft/s (lowest points also within 6 ft of cluster at 0.5 ft/s)
- Limited interference between rocks, acting more like single rocks



Wenatchee – Diamond LSPIV Data



Wenatchee – Down V LSPIV Data



Conclusions Part 3

- Wenatchee:
  - Less interactions between the boulders within a single boulder cluster than expected. This was a low flow for Wenatchee (acting more like the "large" not overtopped boulder clusters). But can't really get data at higher flows with these techniques
  - Velocity reduction up to 40-60 ft downstream of cluster [about 10*D of rock]

- Entiat
  - Interaction and recirculation between boulders! Velocity reduced significantly at center of cluster
  - Clusters too close to see impacts of each cluster

Future Work

- Funding for technical guidance on boulder clusters
  - Come talk to me about it!
  - Generalizing the Wenatchee and Entiat data like we did for Project #2

- LSPIV capable drone … could be fun!

Thank you to Steve Kolk and the Wenatchee Office!

Thank you to SCAO for the original project work!

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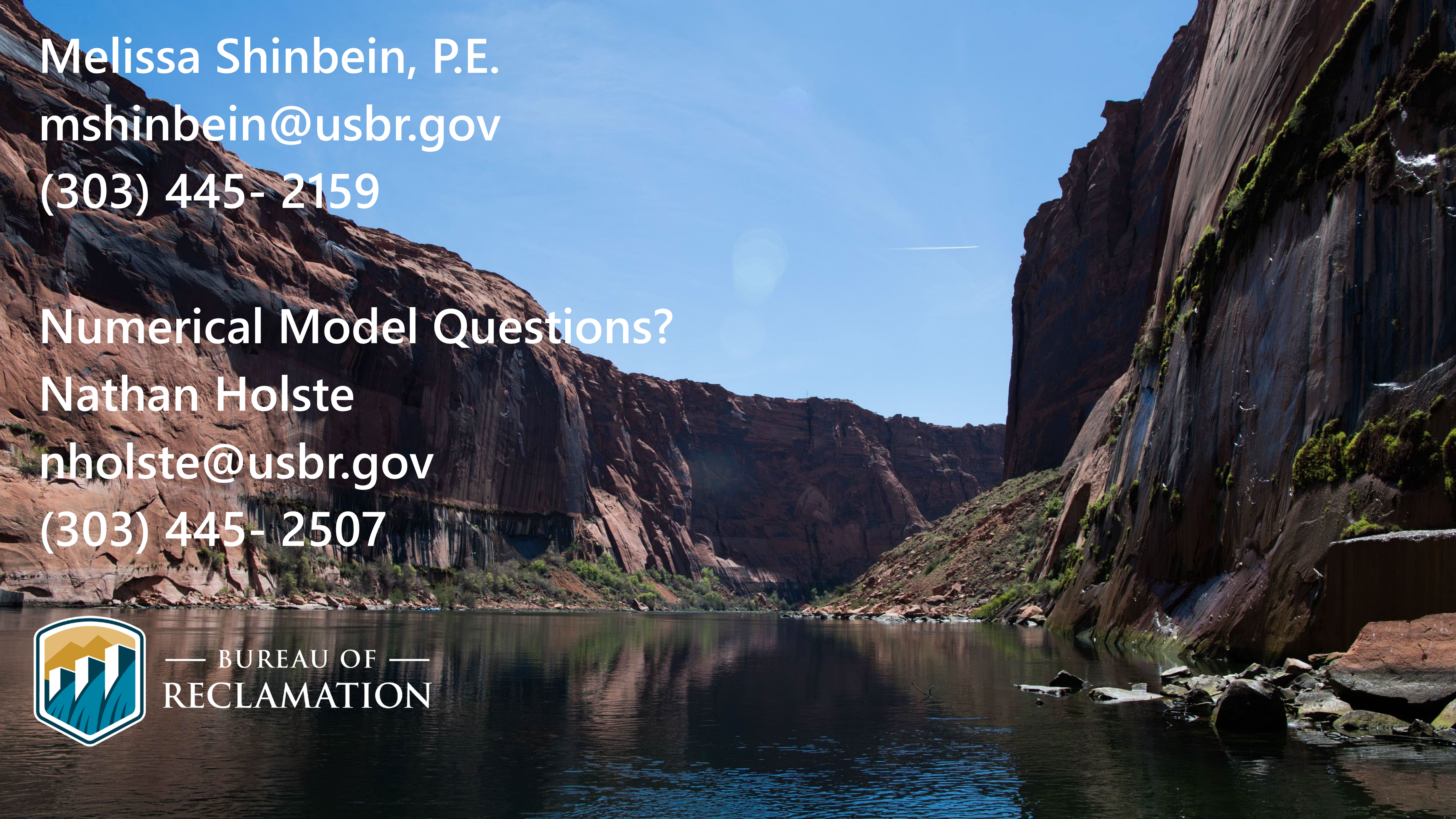
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Numerical Model Questions?
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For those curious…

I did not present on this originally, but I always leave the following slides in for those who wish to see the full list of variables analyzed as part of this study.

Boulder Properties

- Length for each boulder (XB) = measured along flow direction
- Width for each boulder (YB) = measured transverse to the flow direction
- Height for each boulder (ZB) = measured above riverbed
- Width for each boulder cluster (YBC) = measured across widest part of cluster
- Average height for cluster (ZB) = the average height of the rocks in the cluster
- Plan View Area for each boulder (AP-B) = XB * YB.
- Plan View Area for each boulder cluster (AP-BC) = sum of AP-B for each rock within the cluster.
- Plan View Area for each test configuration (AP-BCT) = sum of AP-BC for each cluster used in a test.
- Cross-section Area for each boulder (AXS-B) = YB * ZB
- Cross-section Area for each cluster (AXS-BC) = YBC * ZB
- Cross-section Area for each test configuration (AXS-BCT) = sum of AXS-BC for each cluster used in a test
- Volume for each boulder (VOLB) = XB * YB * ZB
- Volume for each boulder cluster (VOLBC) = sum of VOLB for each rock within the cluster
- Volume for each test (VOLBCT) = sum of VOLBC for each cluster used in a test

Flow Properties

- Upstream Flow Depth for each boulder or boulder cluster (YUS) = the depth measurement(s) at ADV points taken immediately upstream of each boulder or boulder cluster.
- Length of Flow Path along test section (Lx) = 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 (LBx) = for each cluster or single rock, the downstream distance of hydraulic influence was estimated.
- 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 ($\overline{WW}$).
- Flow Plan View Area for each test (AP-Flow) = Lx * $\overline{WW}$.
- Average Flow Depth for each test ($\overline{YY}$) = 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 (AXS-Flow) = average flow depth at the cross-section containing the cluster or single rock (YXS) * W
- Flow Volume for each test (within the test section) (VOLFlow) = AP-Flow * $\overline{YY}$

Dimensionless Analysis

- % Plan View Area Blocked (%AP-Blocked) = AP-BCT / AP-Flow.
- % Cross-section Area Blocked for each cluster or single rock (%AXS-Blocked) = AXS-BC / AXS-Flow.
- Average % Cross-section Area Blocked for each test = sum of %AXS-Blocked for each cluster divided by number of clusters.
- Total % Cross-section Area Blocked for each test (%AXS-Blocked-Total) = [sum of (%AXS-Blocked * LBx) for each cluster] / Lx
- Average overtopping ratio for each test = sum of (YUS / BZ) for each cluster divided by number of clusters.
- % Volume Blocked (%VOLBlocked) = VOLBCT / VOLFlow.

Velocity Analysis

- Vmin – the minimum measured velocity
- V10 – the velocity where 10% is less than or equal to;
- V25 – the velocity where 25% is less than or equal to;
- V50 – the velocity where 50% is less than or equal to (median velocity);
- V75 – the velocity where 75% is less than or equal to;
- V90 – the velocity where 90% is less than or equal to;
- Vmax – the maximum measured velocity;
- VAVG – the average velocity for the test section;
- SDV – the standard deviation of the velocity distribution.
- Interquartile ranges: (1) Vmax and Vmin, (2) V90 and V10, and (3) V75 and V25.
- Velocity ratios comparing boulder tests to the baseline, such as: VRAVG = VAVG_boulder/ VAVG_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.