Physical and Numerical Model Testing of Boulder Cluster Configurations in Urban Channels

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Abstract

Boulders and boulder clusters are often used in fish passage design because they create topographic variability that produces variability in the hydraulic flow field in an otherwise uniform channel. The largest hydraulic effect occurs when the water surface is near the elevation of the boulder crests. Further increases to the discharge and water surface elevation cause flow to overtop the boulders, which disrupts the downstream wake zone. Deeply submerged boulders may provide local velocity refuge near the bed, but do not have a significant effect on the depth-averaged velocity.

The Bureau of Reclamation's Hydraulics Laboratory in Denver, Colorado constructed a distorted Froude-scale physical hydraulic model of a preliminary design for the low-flow channel portion of the Los Angeles (LA) River (Holste et al. 2019; Shinbein and Holste 2020). The purpose of the model was to investigate the placement of boulders in urban channels to provide the best habitat suitability for steelhead. The physical model was designed with a vertical scale of 1:4 and horizontal scale of 1:8 (distortion factor of 2) to provide sufficient water depth for data collection around the boulders. Selected boulder configurations were also analyzed at prototype scale with a two- dimensional (2D) numerical model.

Large and small boulders were tested in a physical hydraulic model using Acoustic Doppler Velocimetry and Large-Scale Particle Image Velocimetry. 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 for minimum, quartiles, and maximum values.

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 30-35%. 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. Due to these high flows, boulders and boulder clusters installed in the LA River will need to be anchored, to prevent them from being swept downstream. In some environments, some movement of boulders is allowable as they continue to provide habitat, regardless of location and may be replaced by other boulders that move from upstream. However, the LA River does not have an upstream sediment source for the boulders. Boulders were not anchored into the physical model for ease of changing configurations. As higher flows were not tested, boulder movement was not observed during testing.

This year, additional funding was provided by Reclamation's Science and Technology program to create a boulder cluster design guidance to assist river restoration practitioners in meeting fish habitat objectives and expand on numerical modeling.

Introduction

This paper aims to summarize work previously completed in two studies concerning the usage of boulder clusters for fish passage (Holste et al. 2019; Shinbein and Holste 2020). Boulders protrude into the flow causing a backwater effect immediately upstream and a downstream, with a low velocity wake zone in the lee of the boulder. Flow separates when approaching the boulder and accelerates around the left and right side (and over the crest if the flow depth exceeds the boulder height). The flow separation around the boulder providing hydraulic refugia 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.

A physical model tested various boulder cluster configurations and obtained a robust dataset to describe the depth, velocity, and flow field. The prototype scale was analyzed with a 2D numerical model for one boulder cluster configuration. Results from these studies informed the design for the Los Angeles (LA) River Pilot Project that was funded by a grant from the California Wildlife Conservation Board and led by the non-profit Council for Watershed Health with assistance from Stillwater Sciences and the City of LA. The purpose of these physical model studies was 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.

Experimental Setup and Methods

Physical Model Design

A physical hydraulic model of a LA 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 LA 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 (Figure 1).

Figure 1. Template system used in model construction. For more information, please see Holste et al. 2019.

Data Collection Methods

To best capture the impact of boulders on the flow field, both an acoustic doppler velocimeter (ADV) and large-scale particle image velocimetry (LSPIV) methods were utilized.

Acoustic Doppler Velocimeter (ADV): The primary function of the ADV was to take point velocity and depth measurements in a grid around each of the rocks and throughout the channel (Figure 2). The baseline grid consists of four transects and was kept the same for all tests, assuming there was no overlap with boulder clusters. ADV measurement points were added as needed based on the geometry of the cluster to create a grid around each rock.

This model utilized a Nortek Vectrino Plus with an N-8513 receiver head. Samples were collected in Nortek's Vectrino Plus software and processed via WinADV software (Wahl 2013).

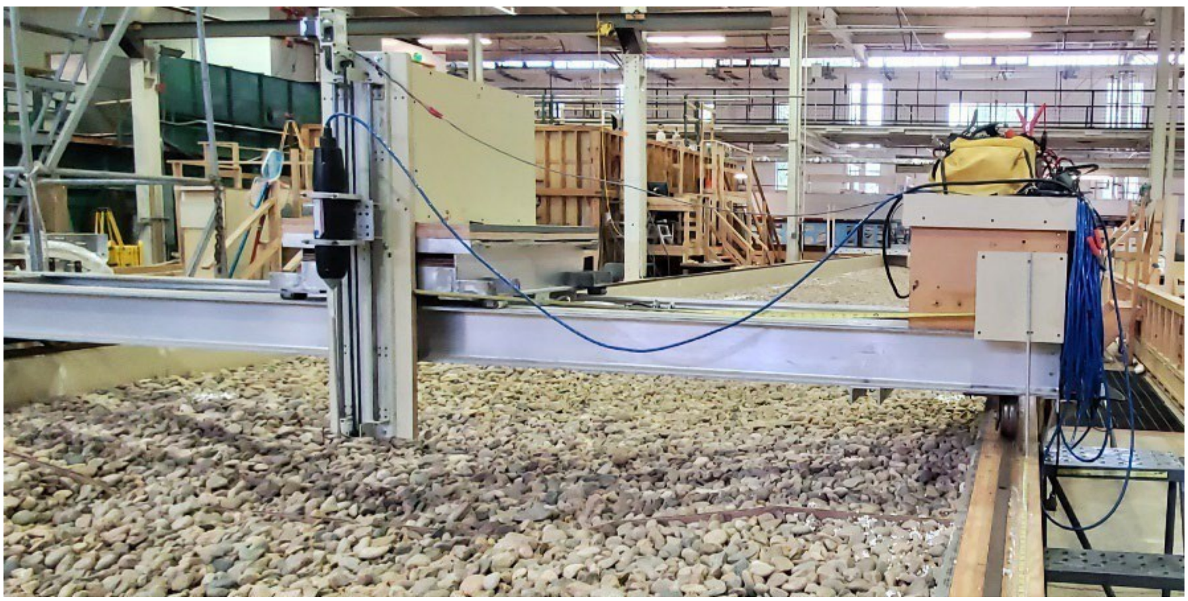

Figure 2. ADV mount in the physical model. The ADV can move horizontally and laterally along length and width of the model. For more information on data collection methods, please see Holste et al. 2019.

Large-Scale Particle Image Velocimetry (LSPIV or PIV): LSPIV methodology captured surface velocities for the entire length of the channel test section. Seeding material was evenly dispersed into the channel until a minimum of 10 seconds of full coverage on the water surface was obtained. To capture this data, a GoPro Hero6 sampled at a rate of 30 frames per second. Afterwards, frames were separated into individual images using RIVeR 2.2 (Patalano 2017). These frames were then processed using PIVLab software (Thielicke and Stamhuis 2014). After processing, PIVLab output were analyzed with TecPlot to create velocity maps of the water surface.

Test Matrix

Baseline (no boulders), and large and small boulders were utilized in four different configurations at three different flow rates. The configurations include single rocks and clusters, which are groupings of rocks closely together in the channel (Figure 3). Additionally, the density of the rock clusters was modified 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 distributed throughout the channel, "medium-high density" was 6 rocks in various locations, "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 so submerged that they no longer impact the water surface. All small rocks were selected to be overtopped at the middle flow condition and fully submerged at the highest flow condition (Shinbein and Holste 2020).

Figure 3. 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. For more information, please see Holste et al. 2019.

Numerical Model

Initial numerical model simulations performed with HEC-RAS 2D evaluated the upstream V configuration installed in the prototype LA River within a roughened low-flow channel. Those results are presented in this paper. Additional simulations performed with SRH-2D tested a combination of different boulder types, and an ongoing study will develop a numerical model of the physical model configurations to compare results. The HEC-RAS 2D numerical model used a digital elevation surface with the boulders represented as hemispheres within the terrain. A mesh with 1-foot cell sizes represented topography near the boulders, which transitioned to 2-foot cells further from the boulders and eventually 4-foot cells within the low-flow channel in regions not influenced by the boulders. Modeled prototype discharges for fish passage analysis varied from 10 cfs, the assumed minimum flow under future conditions, to 4,000 cfs, the high flow passage design event. For more information on the numerical modeling, please see Holste et al. 2019.

Analysis

Analysis aimed to accomplish two main goals: 1) determine if boulder clusters created resting areas for fish passage, referred to as "Resting Analysis"; 2) present a generalized approach so the boulder cluster physical properties could be non-dimensional and used for more generalized application in the future. For both sets of analysis, ADV and LSPIV techniques were employed to gather data which were then analyzed by WinADV, PIVLab, and TecPlot.

This paper represents a condensed presentation of two previously written papers. Further explanation of analysis performed and results for the resting analysis can be found in Holste et al. 2019. Further explanation for dimensional analysis can be found in Shinbein and Holste 2020.

Resting Analysis

Desirable resting velocity and prototype flow rates in the physical model were set based on data collected on the LA River. The tested flow rates were 300 cfs and 600 cfs. The 300 cfs flow rate represents the approximate capacity of the modified low-flow channel before water spills out onto the adjacent concrete. The 600 cfs flow rate represents the maximum flow rate the physical model could sustain without overtopping. Resting conditions were linked to the velocity conditions for adult steelhead (Table 1). A minimum depth criterion of 1 ft was also applied to the dataset where ADV points were recorded.

After ADV and PIV datasets were processed, results were classified according to depth and velocity criteria (Table 1). Velocity results from each boulder configuration were compared to the baseline dataset, or the roughened channel without the addition of boulder clusters, to determine the most effective configuration at the most economical density.

Table 1. Velocity values used for fish passage analysis (Bell 1991; Caltrans 2007; Allen 2015).

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

Dimensionless Analysis

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 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).

Boulder Properties: Boulder properties describe the dimensions of boulders used in the physical model testing, such as length, width, and height for each boulder. Additionally, this includes plan view area, cross-sectional area, and volume for each boulder, boulder cluster, and sum of all clusters used for higher density configurations. Due to space constrictions, these results will not be presented within this paper. Please see Shinbein and Holste 2020 for the comprehensive analysis and results.

Flow Properties: Flow properties focused on the impacts of boulder(s) on the hydraulics both immediately surrounding the clusters and overall test section. These results were assessed using the ADV data points and include parameters such as length of flow paths and influence downstream of clusters. Due to space constrictions, these results will not be presented within this paper. Please see Shinbein and Holste 2020 for the comprehensive analysis and results.

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 and flow conditions. This would enable other channel sizes to use the dataset if the percent blockage is known. In addition to percent plan view area blocked, percent cross-sectional area, volume, and overtopping ratio were calculated. Please see Shinbein and Holste 2020 for the comprehensive analysis and results.

Velocity Analysis: Cumulative Distribution Function (CDF) and Probability Distribution Function (PDF) curves were generated for each configuration. The velocity ratios of each configuration were derived from CDF for minimum, quartiles, and maximum values. These values were then related to the corresponding baseline flow rate. 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 sake of page limitations, only some of the results were discussed in this paper. Please see Shinbein and Holste 2020 for the comprehensive analysis and results.

Results

Resting Results

The baseline condition, or the roughened channel without the addition of boulders, slowed down the velocity of the water when compared to the unlined prototype design. However, roughening the channel did not slow velocities enough to qualify as resting zones besides at the very edge of the banks (Figure 4 and Figure 5). When applying the velocity criteria from Table 1, the baseline configuration offered approximately 23% fraction suitable for resting at 300 cfs (Figure 6).

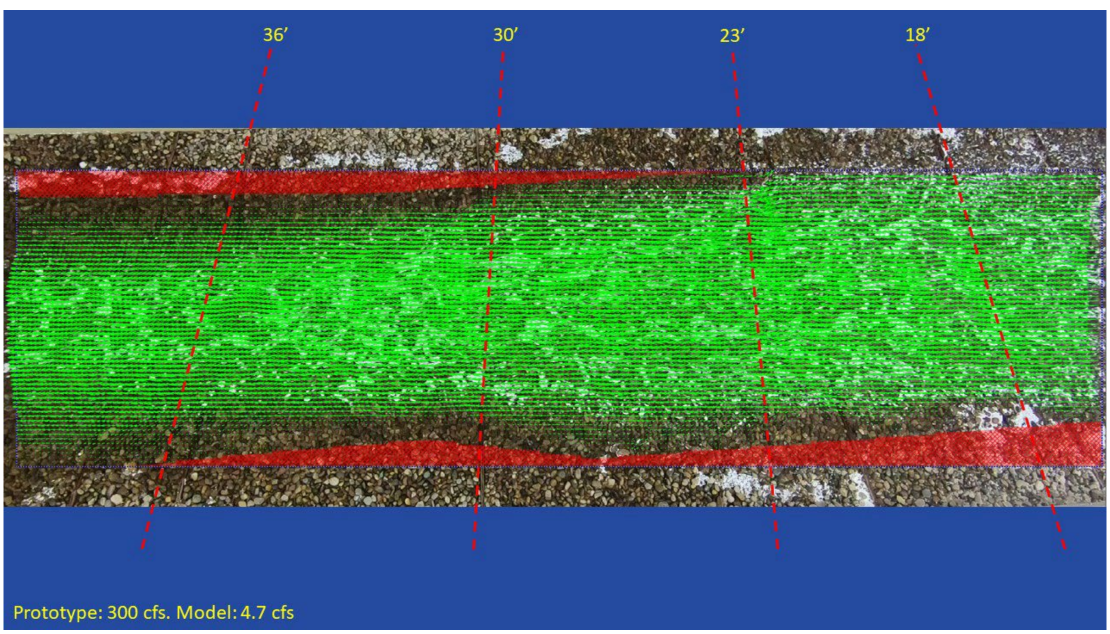

Figure 4. PIVLab output of velocity vectors at 300 cfs baseline flow through the channel. Baseline ADV measurement transects are indicated with dotted lines. Distances marked in figure represent offset downstream from the start of the model. Red areas are "masked" portions that are either too shallow or too reflective for analysis in PIVLab. For more results, please see Holste et al. 2019.

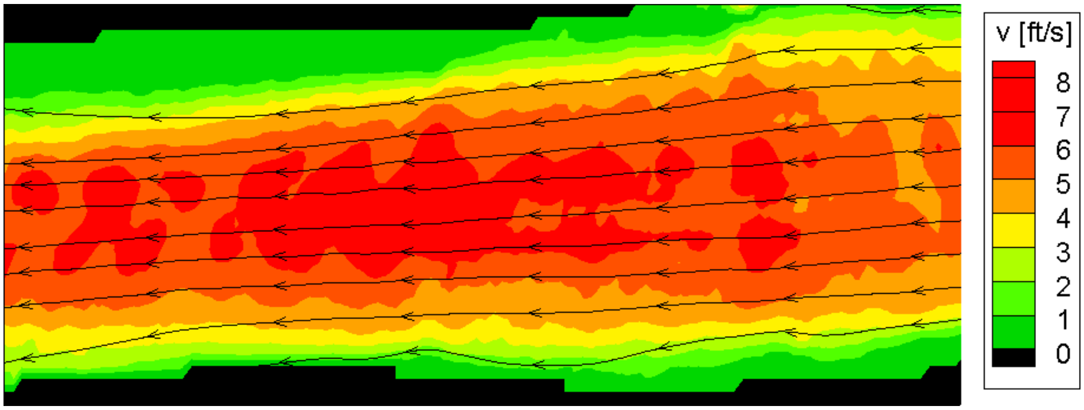

Figure 5. TecPlot output for velocity at 300 cfs baseline flow through the channel. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab. For more results, please see Holste et al. 2019.

Once the boulder clusters were added, the same analysis was applied to each configuration and density at every flow rate to compare the fraction suitable using the velocity criteria in Table 1 (Figure 6). When compared to the baseline, all rock configurations at all densities had a higher fraction suitable for resting, except for the single rock configuration at the higher flows. The upstream "V" and downstream "V" configurations were the most effective per rock and performed similarly to each other. For the lower flow rate, the upstream "V" cluster performed at 73% efficiency for the high (4 clusters, 12 rocks) density and in the mid-50% range for both low (2 clusters, 6 rocks) and medium (3 clusters, 9 rocks) densities (Figure 7 and Figure 8). The downstream "V" cluster performed similarly at the high and low densities, however at the medium density (3 clusters, 9 rocks) the configuration peaked to 67% fraction suitable, 10% higher than the upstream "V" for the same number of rocks, thus performing best for the number of rocks utilized. Afterwards, boulder clusters were imported into the numerical model for comparison (Figure 9).

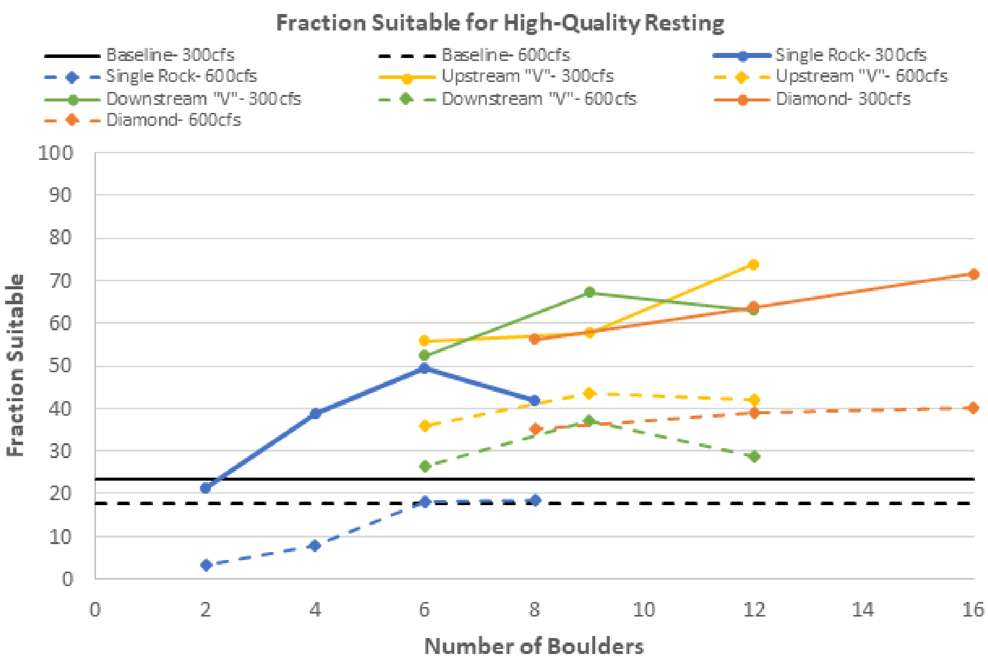

Figure 6. Fraction suitable for high-quality resting (<3 ft/s) versus number of boulders for both flow rates tested (300 and 600 cfs, prototype). All 300 cfs are denoted in solid lines. For more discussion on the configurations not presented in this paper, see Holste et al. 2019.

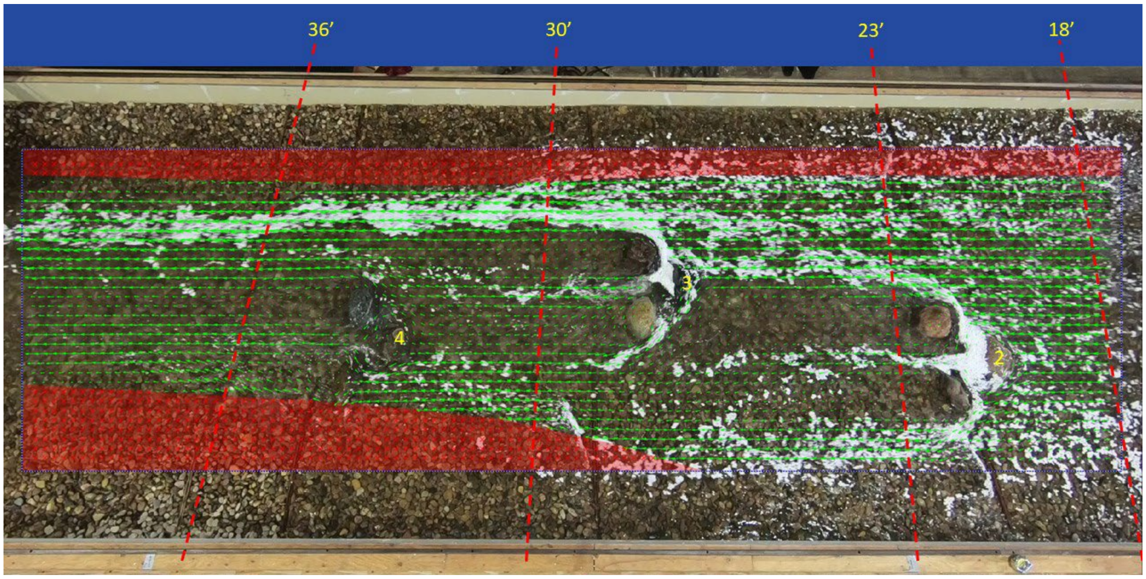

Figure 7. PIVLab output of velocity vectors at 300 cfs at the upstream “V”, medium density (or 3 cluster) configuration through the channel. Baseline ADV measurement transects are indicated with dotted lines, rock cluster numbers are denoted in yellow (2, 3, 4). Cluster 1 was removed for the medium density configuration. Red areas are “masked” portions that are either too shallow or too reflective for analysis in PIVLab. For more results, please see Holste et al. 2019.

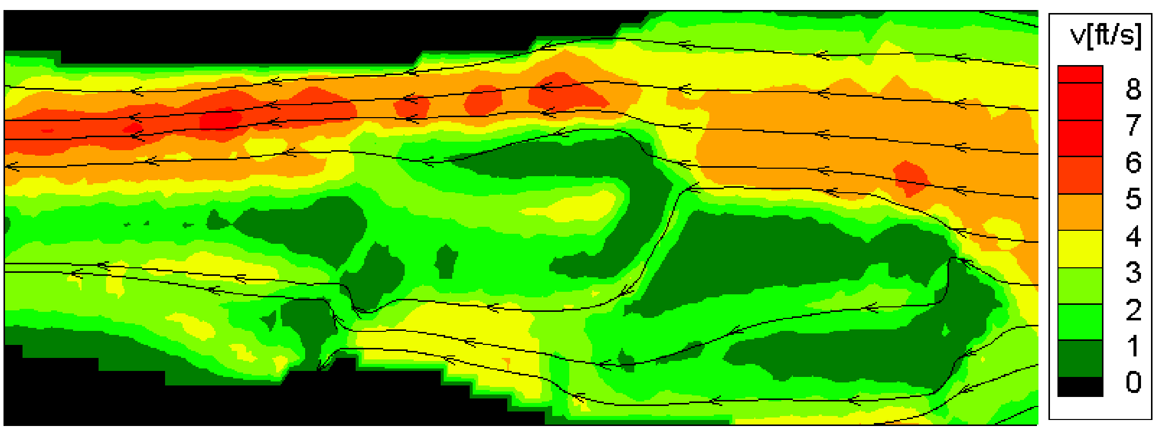

Figure 8. TecPlot output for velocity at 300 cfs at the upstream “V”, medium density configuration. Desired resting areas (< 3 ft/s) are denoted in green. Black spaces denote areas too shallow for analysis and were masked in PIVLab. For more results, please see Holste et al. 2019.

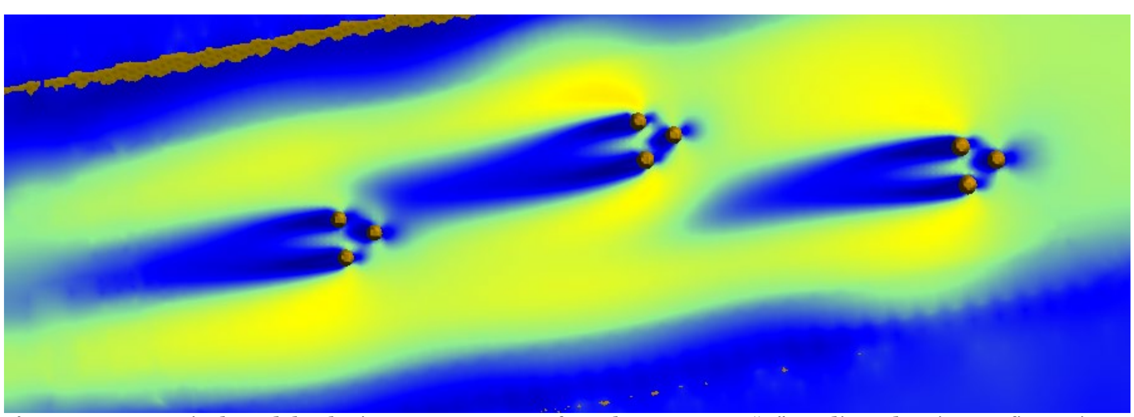

Figure 9. Numerical model velocity output at 300 cfs at the upstream “V” medium density configuration. Darker blue colors represent lower velocity while brighter yellow represents higher velocity. For more results, please see Holste et al. 2019.

This process was repeated for low- and high-quality resting areas. Low-quality resting represents velocities of 3-5 ft/s. Thus, all velocities under 5 ft/s were deemed suitable for that analysis. For more discussion of these results, please see Holste et al. 2019.

Figure 10 and Figure 11 present results from the numerical model simulations. The boulders occupy a relatively small area and are therefore comparable to a roughened meandering channel without boulders. However, the boulders consistently increase the quantity of high-quality resting habitat at nearly all flows. Mapping the velocity zones demonstrates that the numerical model produces similar results to the physical model, where low velocity wake zones form downstream of the boulder clusters. These wake zones provide opportunities for migrating fish to rest while moving through the LA River toward upstream tributaries.

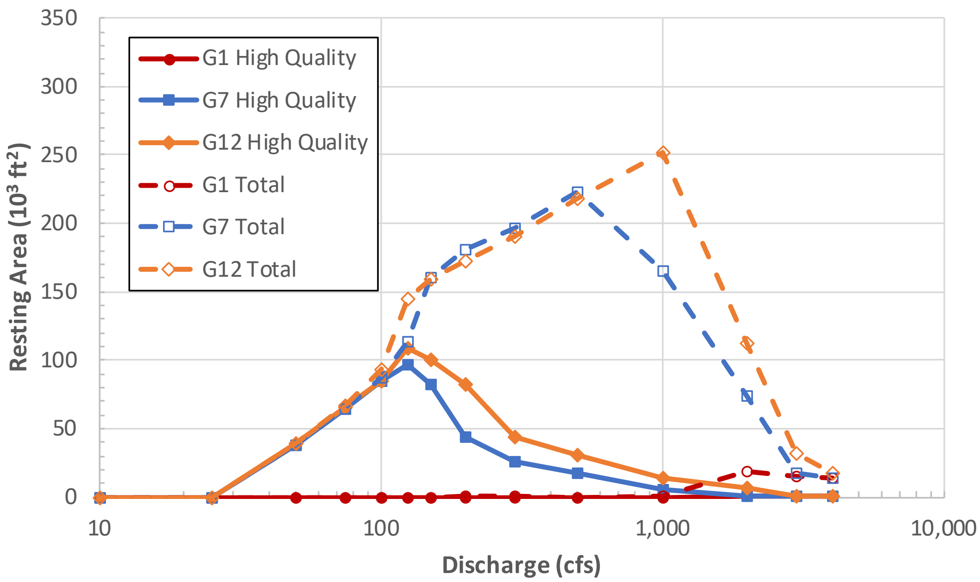

Figure 10. Comparison of high quality and total resting area for three geometry scenarios: existing conditions (G1), a roughened meandering pool-riffle channel (G7), and boulder clusters (G12). For more results, please see Holste et al. 2019.

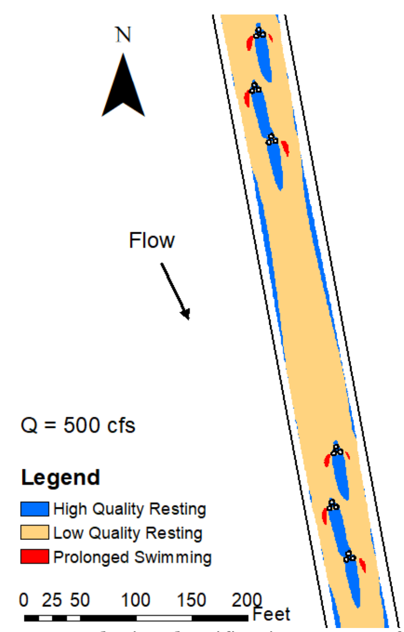

Figure 11. Velocity classification at 500 cfs for upstream V boulder clusters. Depths less than 1 ft are not shown. For more results, please see Holste et al. 2019.

Dimensionless Analysis Results

After the baseline hydraulics were 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. Due to space constraints, only a portion of the results are discussed here. Figure 12 through Figure 14 pertain to the dimensionless parameters of interest plotted against the average velocity ration. The average velocity ratio (VR_{AVG}) is the ratio of the average velocity ($V_{AVGBoulder}$) to the corresponding baseline average velocity ($V_{AVGBaseline}$) for each flow rate (Equation 1). A number less than 1 indicates the velocities within the channel were reduced by the boulder configurations, a number greater than 1 indicates the velocity at this percentile has been increased by the boulder configuration.

$$VR_{AVG} = \frac{V_{AvgBoulder}}{V_{AvgBaseline}} \quad (1)$$

For percent plan view area blocked, upstream and downstream "V" configurations were the most efficient at reducing velocity given the plan view area blocked, echoing the resting results (Figure 12). Overall, 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. However, continued testing is advised to continue to parse out this relationship. For more discussion of these results, please see Shinbein and Holste 2020.

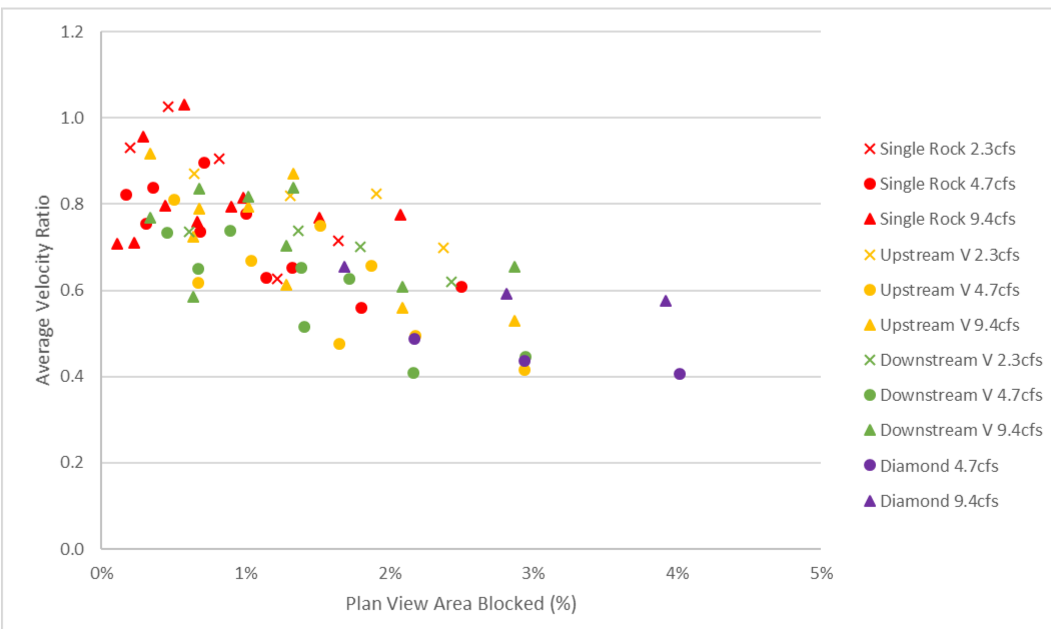

Figure 12. Percent plan view area blocked for every configuration and average velocity ratio. The average velocity ratio is the average velocity per test taken with respect to the corresponding baseline average velocity for each flow rate. Each configuration represents small and large rock tests. For more results, please see Shinbein and Holste 2020.

A similar trend can be seen in the percent cross-sectional area blocked (Figure 13). 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 upstream and downstream "V" performed similarly. The effectiveness of the downstream "V" at reducing velocity 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 30-35% is optimal, since higher percent blockages do not appear to reduce the average velocity. However, continued testing is advised to continue to parse out this relationship.

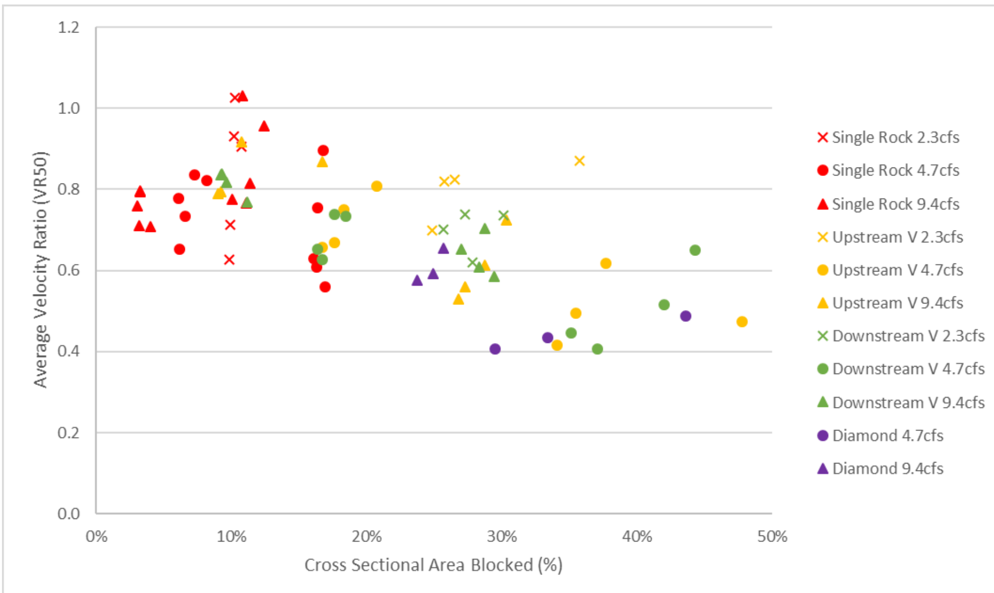

Figure 13. Percent cross-sectional area blocked for all configurations and average velocity ratio. The average velocity ratio is the average velocity per test taken with respect to the corresponding baseline average velocity for each flow rate. Each configuration represents small and large rock tests. For more results, see Shinbein and Holste 2020.

As the percent volume blocked increases, the average velocity ratio decreases regardless of configuration used (Figure 14). 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 improve the velocity ratio when compared to the upstream and downstream "V". When comparing similar scenarios whit the same cross-sectional area blocked, the upstream and downstream "V" have the greatest reduction of velocity.

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.

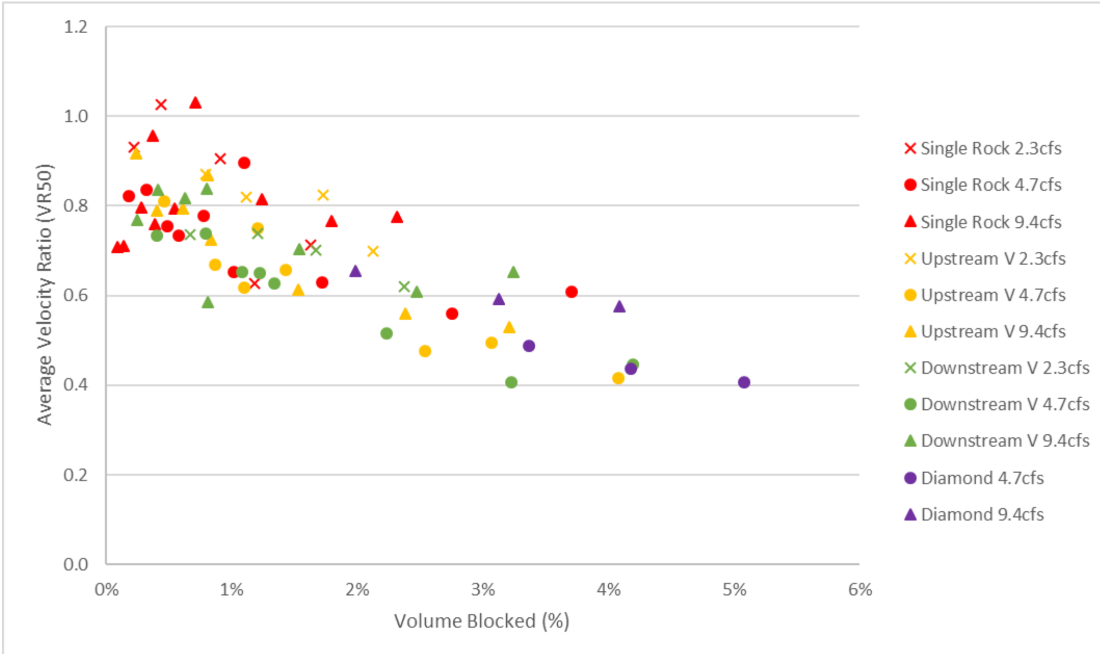

Figure 14. Percent volume blocked for every configuration and average velocity ratio. The average velocity ratio is the average velocity per test taken with respect to the corresponding baseline average velocity for each flow rate. Each configuration represents both small and large rock tests. For more results, please see Shinbein and Holste 2020.

Conclusions and Future Work

Conclusions

As described in Holste et al. 2019, four configurations were tested in the physical model. These configurations were: single rock, upstream “V”, diamond, and downstream “V’. All configurations presented unique hydraulic attributes that would be best suited for varying flow conditions. The downstream “V” configuration was highly effective for the number of rocks used by creating a backwater effect upstream of the clusters. However, this backwater area may impinge on channel freeboard requirements. The upstream “V” configuration was better suited for creating both low- and high-quality resting areas at higher flows. Therefore, the upstream “V” configurations may be a reasonable option for channels that are subject to more frequent high flow events where any resting area between 0 and 5 ft/s is considered acceptable. Additionally, single rocks followed a similar pattern where they performed best where low-quality resting conditions are acceptable, posing an economic advantage in high flow channels. The diamond configuration is not as cost effective compared to the upstream and downstream “V” configurations, but they remain effective and require less rocks. It should also be noted that high densities did not consistently produce more resting area due to rocks constricting flow through the channel. Therefore, rock configurations should be varied based on site-specific conditions such as frequency of high flow events, cost, and freeboard restrictions.

As described in Shinbein and Holste 2020, dimensionless analysis was applied to datasets to generate 1) percent plan view area blocked; 2) percent cross-section area blocked at the single rock or boulder cluster; 3) percent volume blocked. 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 improved with the percentage of plan view area blocked due to the small percentages tested. 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%.

For more information on all configurations tested, analysis performed, and subsequent conclusions please see Holste et al. 2019 and Shinbein and Holste 2020.

Future Work

Existing boulder cluster design information provides general considerations, but do not provide quantitative data or methods that can be implemented to design a project and analyze whether it is effective for achieving the desired results. Work completed and described above included physical and numerical modeling to analyze the effect of boulder clusters on depth, velocity, and fish habitat. The scope of the previous work did not include synthesizing qualitative design guidelines with the quantitative model results. Therefore, it is difficult for those not involved in the model studies to apply the results to new projects.

Further refinement of the boulder cluster designs will help demonstrate the functionality of the concept as a low-cost alternative to high complexity prescriptive design methodologies. The immediate benefit of this project will come in the form of lower design cost for similarly channelized urban environments. Recently, an effort to develop a Boulder Cluster Design Guideline document was funded through Reclamation’s Science and Technology program. This documentation effort will commence in 2023.

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