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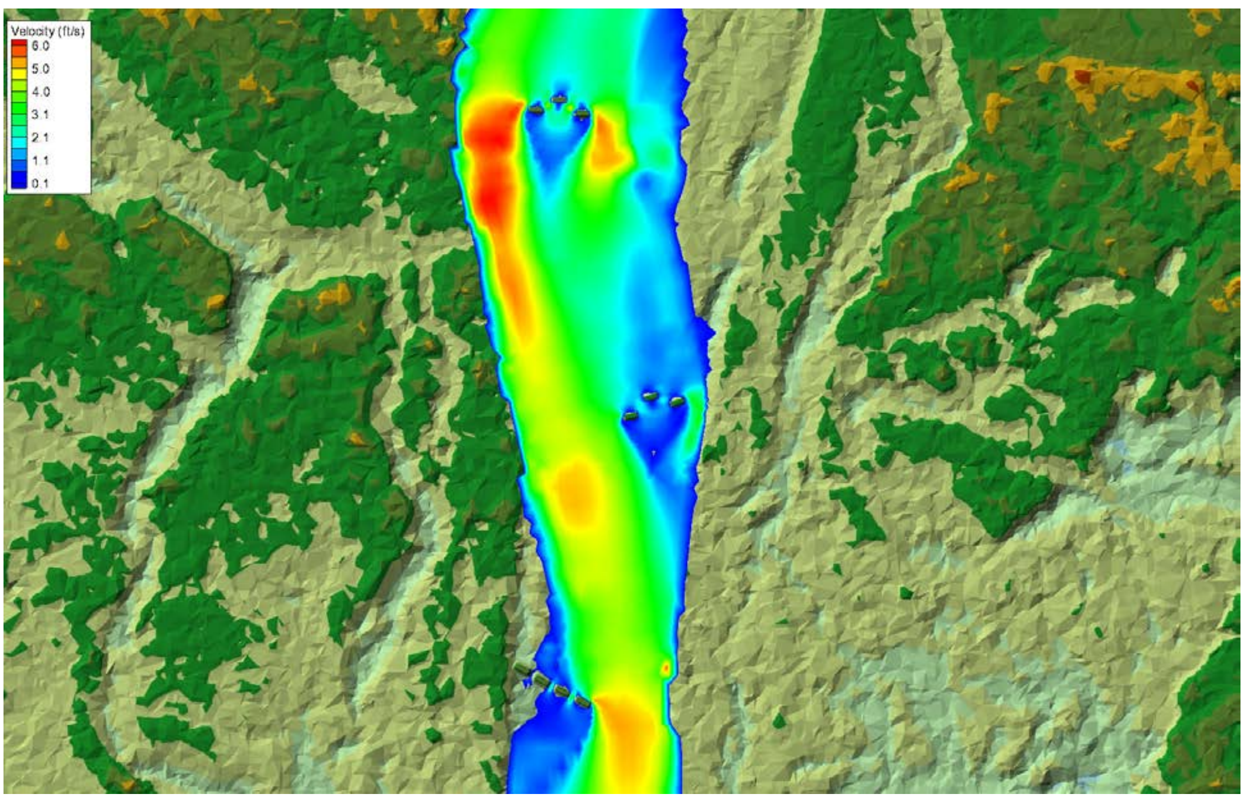
Representation of Large Wood Structures Using a Numerical Two-Dimensional Model

Research and Development Office
Science and Technology Program
Final Report ST-2019-1756-01



U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

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14. ABSTRACT

Large wood has been widely used in stream and watershed restoration projects due to the many ecological benefits it offers. However, its use in streams has unresolved challenges regarding its impact to stream morphology, safety and risk, as well as, design and modeling uncertainties. Large wood structures are being incorporated into project designs at a more frequent rate today than ever before. Hydraulic model results are instrumental in choosing structure type, placement, design parameters, and overall benefit. However, accurately representing the large wood geometry, force-balance equations, and structural evolution through hydro-dynamics modeling can be challenging. There are several ways to incorporate these structures into a hydraulics model, but the validation between what the model outputs and what is observed in the field is still being resolved. Having a better understanding of the effects of implementing these types of structures through improved numerical model representation will aid in ensuring the design and effectiveness of stable wood structures. Increasing confidence

in how to numerically represent the hydraulic effects of large wood structures will help project managers and designers alike by driving down inflated factors of safety resulting in better, faster, and cheaper installations.
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Neil Lassettre and Mark Goin with the Sonoma County Water Agency were instrumental in volunteering both their time to tour Reclamation staff around a few of their project sites as well as providing access to their comprehensive field monitoring data sets for which this research hinged on the use of. Their willingness to help is acknowledged and greatly appreciated.

Acronyms and Abbreviations

LWS – Large Wood Structures

Reclamation – U.S. Bureau of Reclamation

TSC – Technical Service Center

SRH – Sedimentation and River Hydraulics Group at U.S. Bureau of Reclamation

SCWA – Sonoma County Water Agency

2D – Two-dimensional

SRH-2D – Two-dimensional sediment and hydraulics model developed by Sedimentation and River Hydraulics Group at the U.S. Bureau of Reclamation

SMS – Surface-Water Modeling System software from Aquaveo

n – Manning's roughness

F_D – Drag force

C_D – Drag coefficient

WSE – Water Surface Elevation

ft – feet

cfs – cubic feet per second (ft^3/s)

Executive Summary

An understanding of the importance and need of large wood in river systems has gained significant strength in the research and applied studies of eco-hydraulics in recent history. Large wood structures are being incorporated into habitat restoration project designs at a more frequent rate today than ever before. There is usually a significant impact to the local hydraulics with the addition of these types of structures that drives their geomorphic influence. Successful restoration projects require an understanding of the relationship between the structure, resultant hydraulic processes, and eventual geomorphic forms. Having greater confidence in how to best represent these features numerically will aid in their design helping drive down inflated factors of safety resulting in better, faster, cheaper installations as well as ensure feature effectiveness, stability, and longevity.

The Bureau of Reclamation partnered with the Sonoma County Water Agency to research how to best represent large wood structures in a depth-averaged two-dimensional numerical hydraulic model (SRH-2D) by using a selection of methodologies through a matrix of varying model parameters and techniques. By applying the results of this sensitivity analysis to a field data set it was determined just how applicable two-dimensional hydraulics modeling can be in representing large wood structures. It was determined that multiple techniques can be utilized to represent hydraulic structure effects reasonably well, but it is not yet known if the parameterizations used are applicable to all types of installations on all types of river systems. Recommended next steps would be to apply what was learned to other types of structures on other river systems.

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Introduction

Large Wood Structures (LWS) are widely used in stream and watershed restoration projects due to the many ecological benefits they offer; they are being incorporated into project designs at a more frequent rate today than ever before. They have been shown to provide excellent fish habitat for a variety of life stages and species by developing deep scour pools with associated tailout spawning areas as well as complex cover (Saldi-Caromile et al., 2004). They also add much needed organic carbon into the system (Wohl et al., 2016). However, their effect on the stream morphology and stream hydraulics is complex and difficult to predict without the use of numerical models. There is usually a significant impact to the local hydraulics with the addition of these structures that drives their geomorphic influence. Numerical hydraulic model results are instrumental in choosing structure type, placement, design parameters, and overall benefit. Successful restoration projects require an understanding of the relationship between the structure, resultant hydraulic processes, and eventual geomorphic forms. However, accurately representing the large wood geometry and structural evolution through hydro-dynamics modeling can be challenging.

There are several ways to incorporate these structures into a hydraulics model, and although the resultant patterns are inherently sensible to what would be expected, the results from the numerical models have not been quantitatively validated with field observations. Having a better understanding of the model limitations along with the effects of implementing these types of structures through improved numerical model representation will aid in ensuring the design and effectiveness of stable wood structures. Increasing our confidence in how we numerically represent the hydraulic effects of large wood structures will help project managers and designers alike by driving down inflated factors of safety resulting in better, faster, and cheaper installations.

Modeling Large Wood Structures

Two-dimensional numerical hydraulics modeling is becoming more common and is far superior to one-dimensional models in examining the hydraulic effects of large wood structures. The advantage of using two-dimensional models in habitat restoration projects is their capability of reproducing the detailed flow features, such as transverse flows, eddies, velocity gradients, and other complex flow patterns found within streams (He et al., 2009). Modeling these structures in two dimensions allows for a more detailed analysis of the flow stages, depth-averaged velocity magnitudes and vector directions, shear stresses, and bed scour, all of which are common parameters when evaluating habitat suitability and structure stability.

Model Selection

This research used SRH-2D as its modeling platform. SRH-2D is a model that is developed and maintained by the Bureau of Reclamation’s (Reclamation) Sedimentation and River Hydraulics Group at the Technical Service Center (TSC) in Denver, Colorado. SRH-2D is a two-dimensional (2D) fixed or mobile-bed hydraulics and sediment transport model for river systems (Lai, 2008). This research made use of only the fixed bed hydraulics module. SRH-2D solves the depth-averaged dynamic wave equations with a depth-averaged parabolic turbulence model using a finite-volume numerical scheme. The model adopts a zonal approach for coupled modeling of channels and floodplains; a river system is broken down into modeling zones (delineated based on natural features such as topography, vegetation, and bed roughness), each with unique parameters such as flow resistance. SRH-2D adopts an unstructured hybrid mixed element mesh, which is based on the arbitrarily shaped element method of Lai (2000) for geometric representation. This meshing strategy is flexible enough to facilitate the implementation of the zonal modeling concept, allowing for greater modeling detail in areas of interest that ultimately leads to increased modeling efficiency.

Study Approach

Reclamation partnered with the Sonoma County Water Agency (SCWA) in Santa Rosa, California to research how to best represent large wood structures with a two-dimensional numerical hydraulics model using a two-phased approach. Phase I employed a sensitivity analysis through utilizing numerous methodologies with a matrix of varying model parameters and geometric representation techniques. Phase II compared the various approaches to a field data set to determine the best overall methodology and to recommend a methodology to represent large wood structures in a two-dimensional hydraulic model.

Phase I – Sensitivity Analysis

Site Selection

The sensitivity analysis (phase I) utilized a habitat restoration site on the upper Entiat River in north-central Washington. The reach of river selected, locally referred to as the Stormy Reach, can be characterized as being a slightly-to-moderately sinuous single thread channel with a relatively low gradient, gravel-dominated bed, and active unconfined floodplain (average floodplain width much greater than average active channel width) with high in-channel complexity and lateral controls consisting of alluvial fans, bedrock, and levees that constrain the channel position (Godaire et al, 2009).

The small subset area focused on for the sensitivity analysis features two large wood structures. The upstream structure is intended to deflect flow away from the bank, while the downstream structure splits the flow in the active channel. Two non-uniform, unstructured meshes were generated using Aquaveo's Surface-Water Modeling System (SMS) software. Rectangular elements were used within the active channel with transverse spacing ranging from 5 ft near the structures to 15 ft at the upstream and downstream edges of the model. A combination of triangular and rectangular elements was used to mesh the large wood structures and overbank areas. Six material types were identified within the project area (Figure 1) with Manning's roughness (*n*) values based on previous model calibration efforts (Sixta, 2018) and published literature values (Chow, 1959).

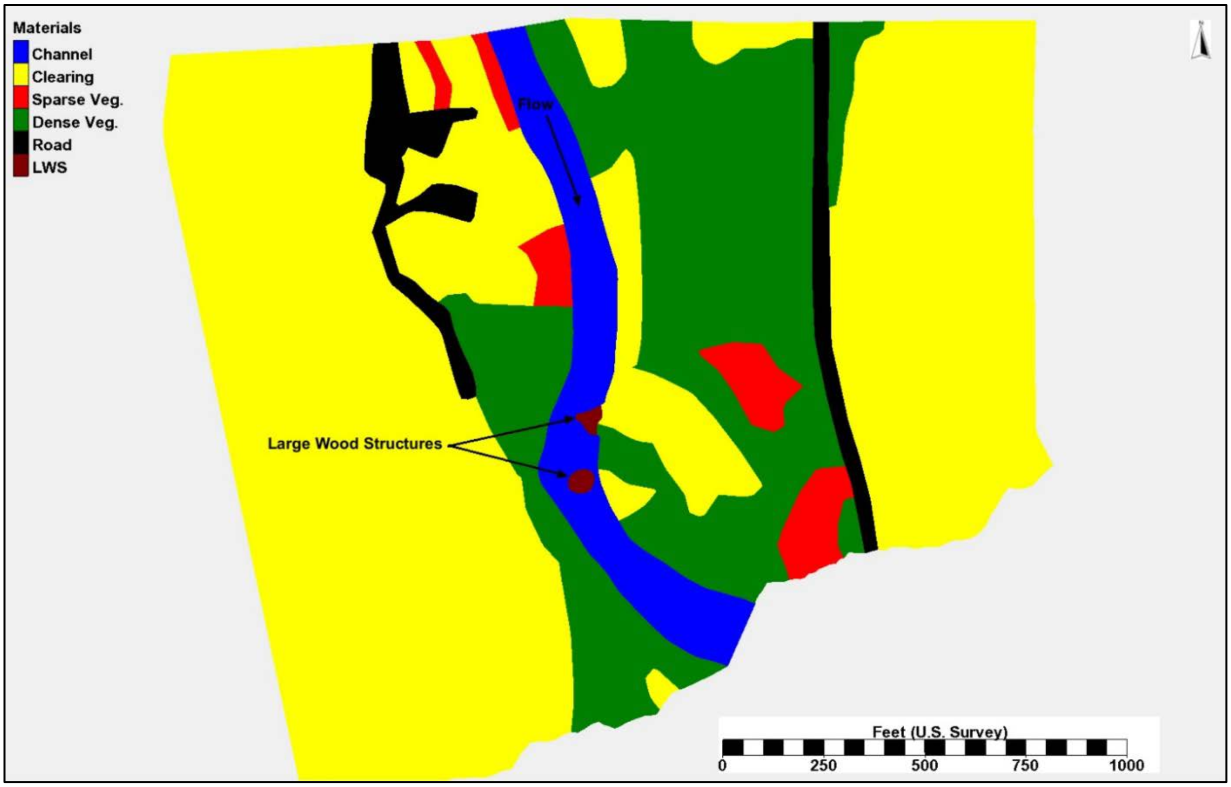

Figure 1. Sensitivity analysis model domain and material delineations.

Sensitivity Analysis Modeling Methodology

For the sensitivity analysis, large wood structures were simulated utilizing four methods that are described in more detail in the paragraphs below.

1) represented as full blocked obstructions (blocking the entire LWS footprint),
2) represented as partial blocked obstructions (blocking a portion of the LWS footprint),
3) increasing the Manning's roughness value (n), or
4) using a drag term in the momentum equation.

Full blocked obstructions were created by raising the model mesh elevations to the design elevation of the top of the large wood structure (Figure 2A). While adding a fully blocked obstruction is a fairly simple way to add LWS to the model mesh, it does not account for structure permeability and may overestimate the increase in water surface resulting from the structures. Assuming the structures are not porous can result in a 10-20% overestimation of drag force (Manners et al., 2007). Furthermore, a fully blocked obstruction will result in a dry (assuming no overtopping) structure footprint, which affects habitat suitability analysis results. Therefore, representing an LWS as a partially blocked obstruction through using 3-5, 10 ft-by-5 ft elevated rectangles spaced roughly 14 ft apart (center-to-center) with 2-ft gaps in-between, was another employed method to try and better simulate the permeable nature of LWS (Figure 2B). The full and partial blocked obstructions were represented with and without increasing the Manning's roughness value.

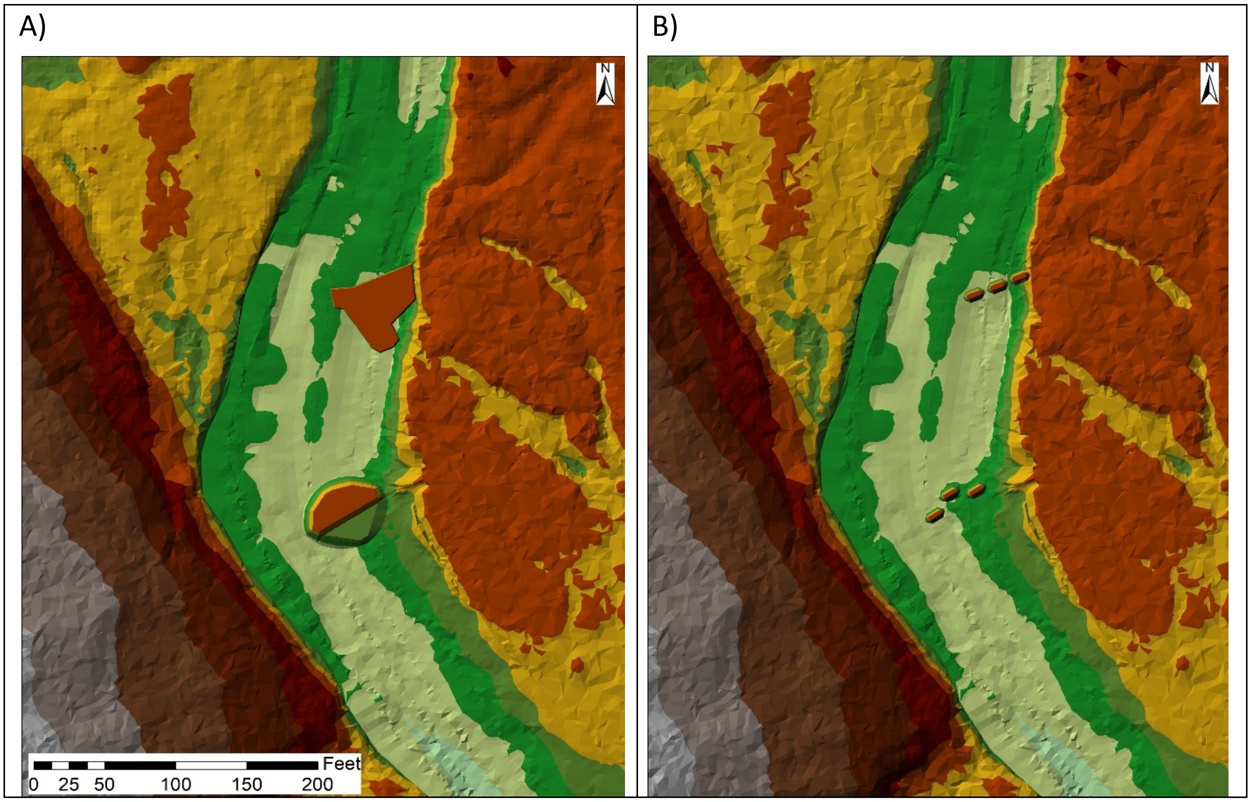

Figure 2. Topographic representations of A) full obstruction and B) partial obstruction.

A third method solely increased the Manning's roughness value within the LWS footprint. Selection of roughness values for complex natural channels with debris is an art based on judgement and experience (Fasken, 1963). Three arbitrary values (0.1, 0.2, and 1.0) were selected based on previous studies and literature value recommendations (Sixta, 2018; Shields and Gippel, 1995).

The relationship between LWS and hydraulic function is quantified through drag force (F_d), which is the difference in pressure the water exerts on the structure from upstream to downstream (Abbe and Montgomery, 1996). LWS can be a significant source of form drag in a river, accounting for 50 percent of the total drag in the channel (Curran and Wohl, 2003). One of the main (and user defined) variables in computing F_D is the drag coefficient (C_d). Increasing the drag coefficient (C_d) within the LWS footprint was the last tested approach. SRH-2D adds additional drag force through internal obstructions. Extra drag forces cannot be explicitly taken into consideration by the 2D depth-averaged approach. Therefore, local flow velocity at or near the obstructions are not correct. Results are intended to show obstruction impacts further away from the structure. Drag force (F_d) is calculated in SRH-2D using Equation 1:

$$F_d = \frac{1}{2} C_d \rho (U^2 + V^2) A_p \qquad \text{Equation 1}$$

Where C_d is the dimensionless drag coefficient, A_p is the wetted cross-sectional area normal to the approaching flow, ρ is water density, U and V are velocity components.

An initial drag coefficient of 1.3 is the upper bound recommended for circular cylinders over the range of Reynolds number typical of natural streams (Hoerner, 1958). The subsequent drag coefficient values were arbitrarily assigned based on the results using $C_d = 1.3$. It is important to note that commonly cited drag coefficients (e.g. Engineering ToolBox, 2004) were developed for the steady motion of flow in infinitely large volumes of fluid and are therefore not quantitatively valid for 2D the depth-averaged processes that are being modeled for several reasons: 1) natural stream flow is not steady nor uniform, 2) velocity varies with depth in the water column, which has a finite depth, and studies have shown this this variation in velocity can have a significant effect on the drag force, 3) a free surface can interact with the flow and the log, 4) logs are "rough", and most importantly, 5) the flow is bounded by the river banks and therefore the presence of the logs can constrict the flow and increase the cross section averaged velocity. The approach velocity is also not well defined in a natural river. It utilizes the average velocity inside of the defined extent, which is another reason why published drag coefficients are not applicable to this modeling technique. Therefore, the drag coefficient was treated as a calibration parameter when used for representing LWS.

A total of 15 model scenarios were executed, including baseline conditions (Table 1). Model response to each method was evaluated based on changes from baseline conditions for water depth, velocity magnitude, and shear stress, which was evaluated through monitoring points at seven locations (Figure 3).

Table 1. Sensitivity analysis matrix.

Scenario No.	Method	Variation
1	Baseline Conditions	n = 0.03; C_d = 0
2	Full Obstruction	n = 0.03
3	Full Obstruction + increase roughness	n = 0.1
4	Full Obstruction + increase roughness	n = 0.2
5	Full Obstruction + increase roughness	n = 1.0
6	Partial obstruction	n = 0.03
7	Partial obstruction + increase roughness	n = 0.1
8	Partial obstruction + increase roughness	n = 0.2
9	Partial obstruction + increase roughness	n = 1.0
10	Increase roughness	n = 0.1
11	Increase roughness	n = 0.2
12	Increase roughness	n = 1.0
13	Increase drag coefficient	C_d = 1.3
14	Increase drag coefficient	C_d = 10
15	Increase drag coefficient	C_d = 25

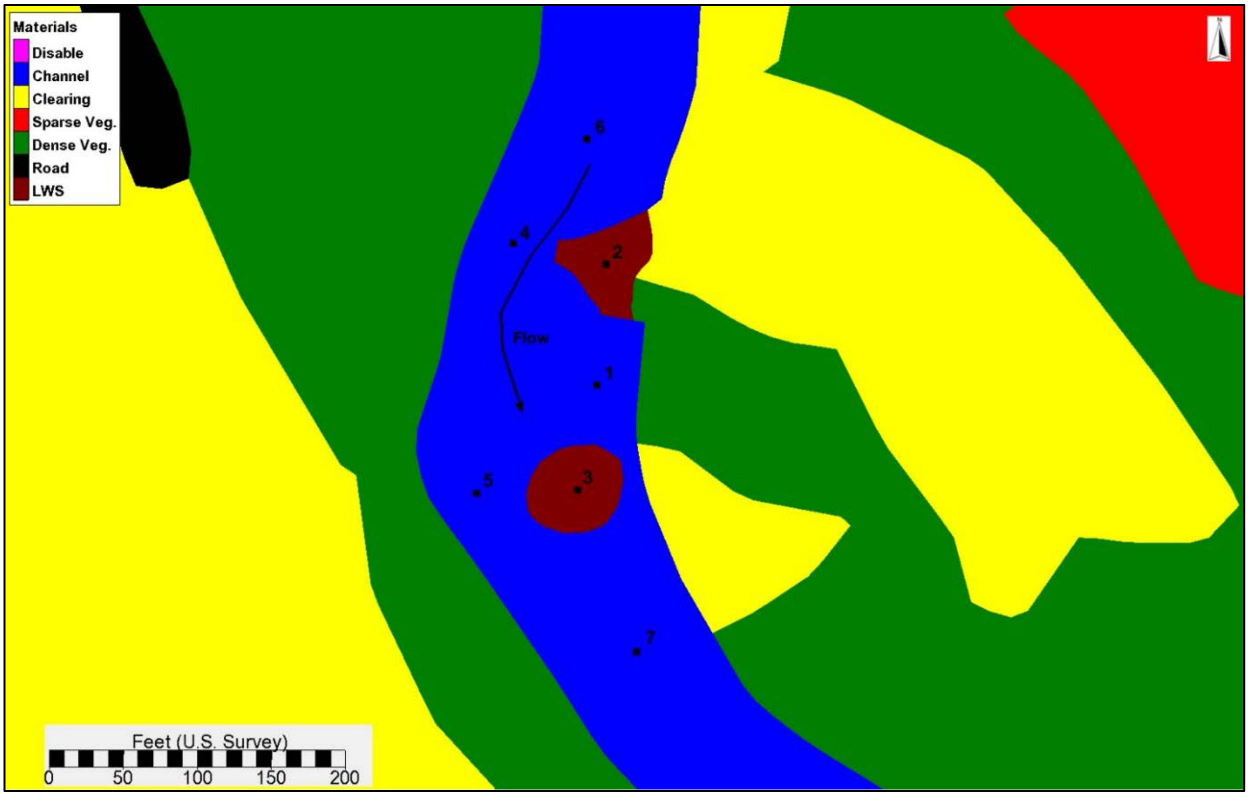

Figure 3. Sensitivity analysis model response evaluation areas.

Sensitivity Analysis Results

Hydraulically, LWS acts as large roughness elements that provide a varied flow environment, reduce average velocity, and locally elevate the water surface profile (Gippel, 1995). More specifically, and based on field observations and hydraulic principles, model results should show an increase in flow depth upstream of the structure and decreased velocity through the structure and in its wake. Meanwhile the velocity magnitude through the main channel and adjacent to the structure should increase due to the localized decease in channel area caused by the structure(s). Baseline conditions, in which structures were not represented, established a control for the sensitivity analysis.

The fully blocked obstructions were not overtopped by the evaluated flow event. Therefore, the cells with varying roughness values were not activated and no differences were observed amongst scenarios 2 through 5. The fully blocked obstructions altered flow depth and velocity magnitude surrounding the structures; an overall increase in depth was observed; velocities decreased upstream and in-between the two structures and increased in the channel adjacent to and downstream of the structures.

Velocity magnitudes through the partially blocked obstructions varied significantly depending on the assigned roughness value, while velocities were seen to increase in the channel adjacent to the structures due to the flow contraction. The flow depth increased at all monitoring point locations except for in the channel downstream of each structure.

Only increasing the Manning's roughness value within the footprint of each structure resulted in what were deemed reasonable trends in flow depth and velocity (Figure 4); however, shear stress is dependent on the roughness value and did not yield realistic results when using artificially high roughness values and should be cautioned against using in design. Three different roughness values were evaluated. The trends were consistent throughout the model domain; however, the monitoring point (Figure 3) that experienced the largest absolute change depended on the applied roughness value. For example, the highest change in depth was in the channel adjacent to the upstream LWS (monitoring point #4) when n = 0.1. When n = 0.2, the highest change in depth was in the channel upstream of both structures (monitoring point #6).

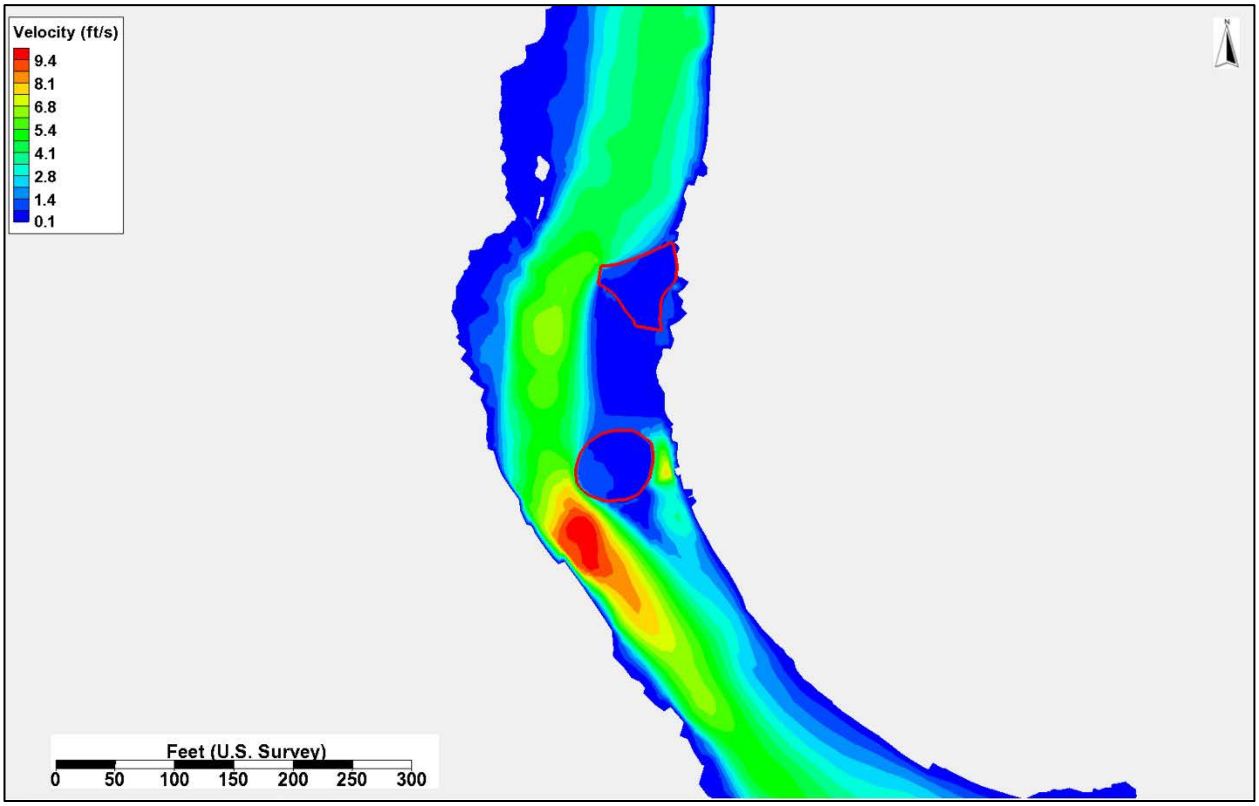

Figure 4. Modeled velocity magnitudes from scenario #11. Flow is from top-to-bottom. LWS footprints are shown in red outlines.

Increasing the drag coefficient resulted in an increase in flow depth at six of the seven monitoring points, an increase in flow velocity adjacent to each LWS, a decrease in velocity within and upstream of the structures, and a decrease in shear stress within the structures. The magnitude of change in these three hydraulic parameters increased as the drag coefficient increased.

Detailed model results from all the sensitivity analysis runs showing the percent change from the baseline conditions are shown in Appendix A.

Phase II – Field Verification

The methods that yielded what were deemed as being the most realistic results from the sensitivity analysis were used to evaluate the overall representation effectiveness on a set of field installations. The only method not utilized in the field case modeling was the partial blocked obstruction based on its arbitrary nature and inconsistencies with repeat application.

Site Selection

Several field sites were available for effectiveness modeling, all of which are located on Dry Creek below Lake Sonoma near Healdsburg, California; there is roughly 13 river miles between Lake Sonoma and its confluence with the Russian River. Numerous wood installations on three distinct project sites, all on the order of less than one river mile in length, were recently installed for the purposes of habitat restoration. Included with each of these projects is an extensive monitoring program that includes the collection of ground surface topography and several hydraulic parameters of interest using a combination of total station survey, an unmanned aircraft system, and velocity flow meter mounted on a wading rod.

The project that was settled on for field verification is locally referred to as the City of Healdsburg site. Located roughly 2 miles upstream of the Russian River confluence, this project site spanned a total of roughly 0.2 miles consisting of a split flow channel running much of the reach length with numerous large wood structure installations mainly in the left channel. The field data set consisted of over 3,500 points, each one of which was tagged with water surface elevation, depth, and velocity. A map showing the location of the large wood installations and data set points is shown in Figure 5, while an example field photo of the installed large wood structures is shown in Figure 6.

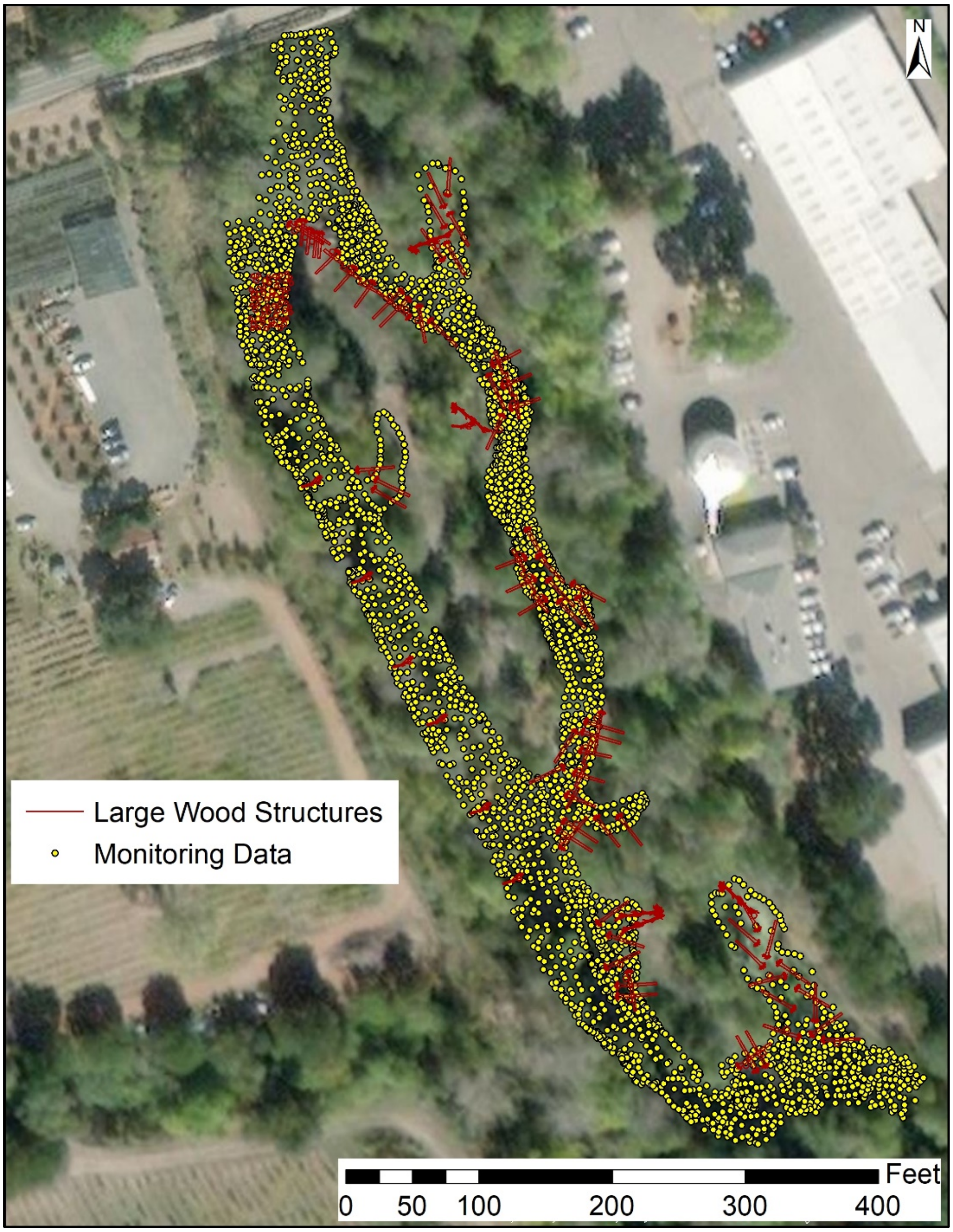

Figure 5. City of Healdsburg field validation site. Flow is from top-to-bottom.

Figure 6. Example large wood structure installations at City of Healdsburg site. Flow at time of site visit was 90 cfs.

Field Verification Modeling Methodology

The tested modeling methodologies were utilized to see how closely the model can represent what was measured in the field. Field data was used to set the model extent for the domain and each LWS. The model domain extended over roughly 900 feet of river. A 90,000-element mesh was generated using 2-ft grid spacing with triangular mesh elements. Three material types delineated roughness extent: channel, floodplain, and LWS (Figure 7).

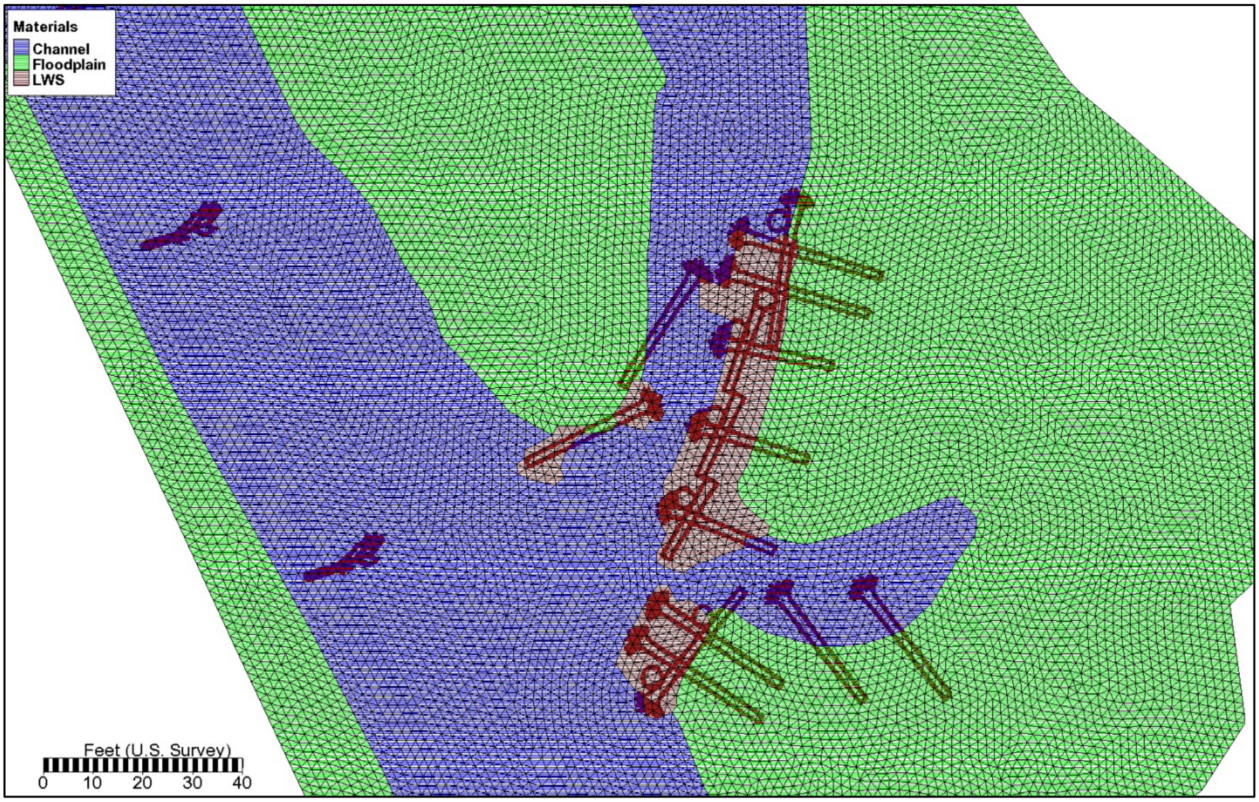

Figure 7. Example area of field verification model mesh showing 2-ft grid spacing and three material types. Flow is from top-to-bottom.

Field data was also utilized to calibrate a 'baseline' conditions model by modifying the channel roughness value (Manning's n) until the observed water surface elevations (at 90 cfs) were closely matched in a part of the project reach that was deemed unaffected by the presence of LWS. A resulting roughness value of 0.04 was used for the main channel (Figure 8). The various modeling methodologies were then employed to the baseline conditions and validation was performed by spatially comparing the field measured water surface elevations and the discharge flux to the modeled values. Given the sporadic and instantaneous nature of velocity data, it was only qualitatively used, ensuring consistent trends between the observed and predicted values were being represented.

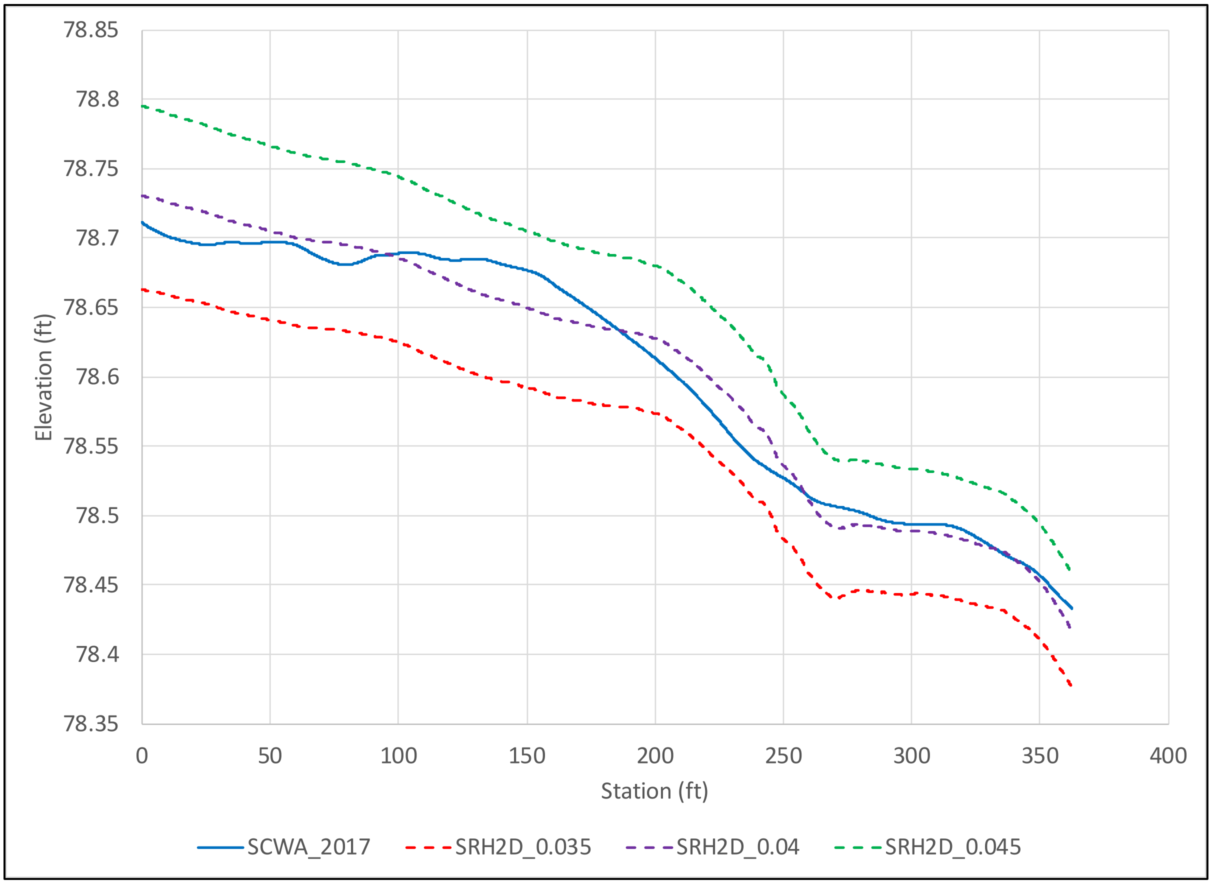

Figure 8. Model calibration to field collected water surface elevations.

Field Verification Results

The applicability of each large wood representation methodology was assessed by looking at water surface elevation along a profile line, flow routing (discharge) through two channels, and velocity distribution patterns surrounding LWS.

Water Surface Elevation

Modeled water surface elevations (WSE) were profiled along 650 ft of the left channel amongst the LWS installations (Figure 9). A composite of results from the most appropriate methods are shown in Figure 10. The drop in the field-observed water surface elevation seen at station 450 is due to a local constriction from an LWS on both the left and right banks. This flow constriction creates a backwater effect upstream; as flow accelerates through the contraction, the water surface elevation quickly decreases.

Although all the methods yielded differences from the field data within tenths of feet, resulting in no clear best representation technique, it was seen that using only roughness (set to a value of 1.0) gave the closest results. Recall the limitation of this method however given the artificially high shear stress values that are calculated from a synthetically high Manning's roughness value. The full blocked obstructions encroached significantly on the channel and was seen to back up water at each constriction, resulting in a stair-step profile.

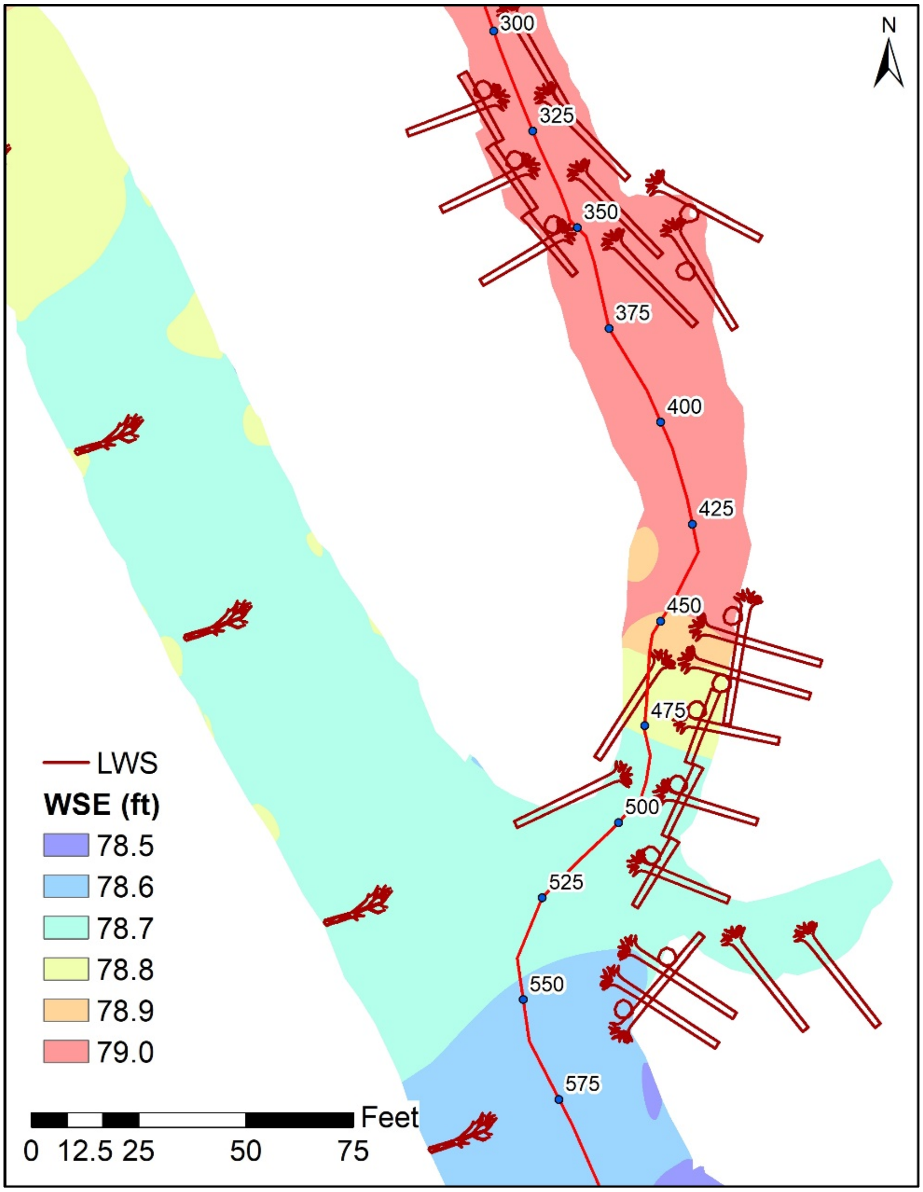

Figure 9. Water surface elevation profile line near downstream confluence.

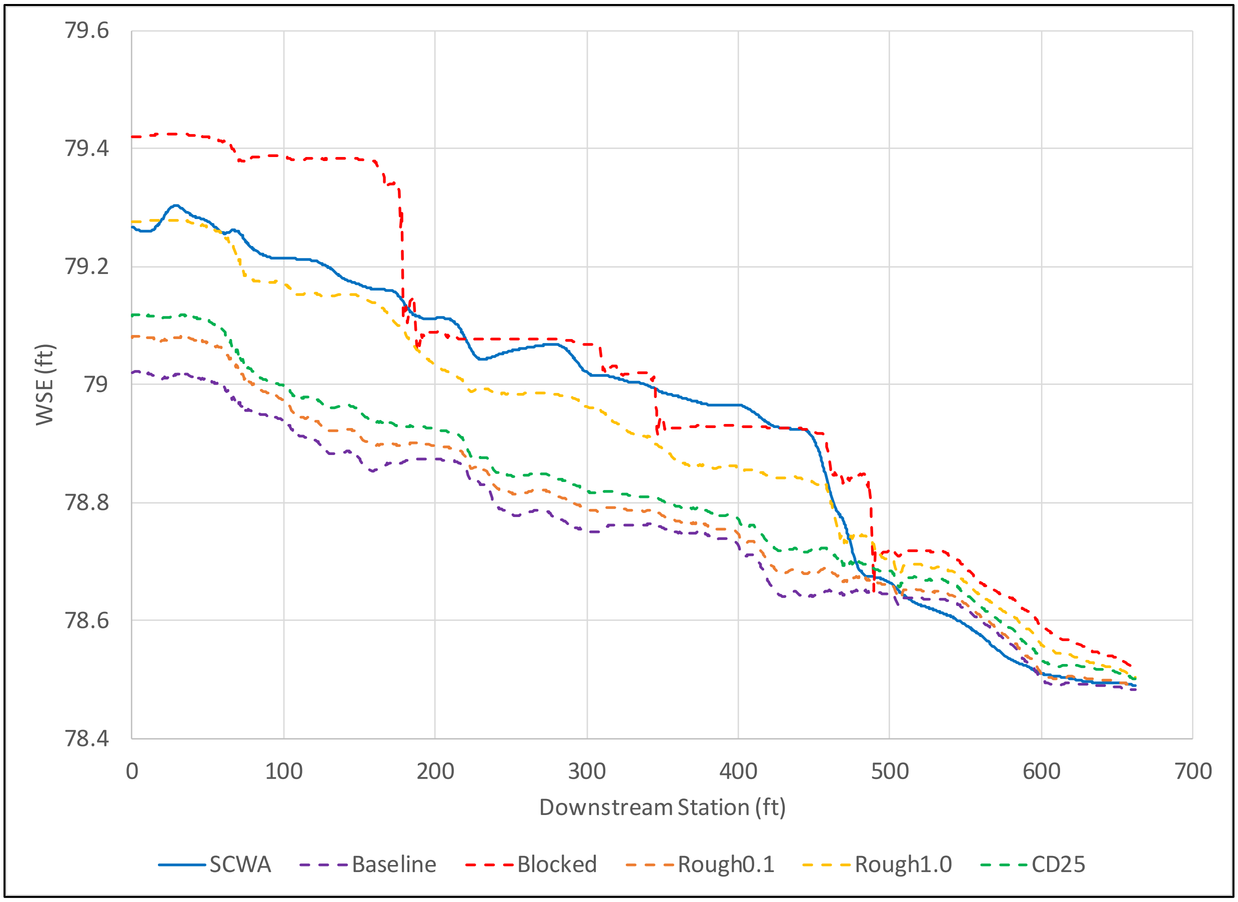

Figure 10. Water surface elevation profile results at 90 cfs from select methods.

Flow Routing

Promising results were seen when looking at the WSE profiles. However, at this particular site it was also important to evaluate if these methods had any impact on how flow was being routed through the reach considering the split flow channel. Monitoring lines were established in SRH-2D in each channel that used the model results to calculate the discharge. These were compared to discharges that were calculated using the field data (depth and velocity), which yielded a roughly even (50/50) distribution. While conservation of mass was observed among all methods, the representation technique was seen to influence the partitioning of the flow between the right and left channels (Table 2). For the case of increasing the roughness value, the higher the value, the further the divergence was from the field observations. This means that the WSE values shown in Figure 8 for the technique of using only roughness to represent LWS with a value of 1.0 are high considering there is less flow in the channel as compared with the field data. It also means that using a roughness value of 0.1 is likely better than using 1.0, even though the WSE's do not match quite as closely, given the more accurate flow split distribution; this lower roughness value would also help yield more reasonable shear stress results. The same trends were seen for increasing values of C_d, the difference being that there was much less of a difference between the WSE profiles for the different values of C_d. The method using full blocked obstructions yielded the biggest difference in flow split values from the measured conditions, and therefore the use of this representation technique is cautioned against.

Table 2. Flow split distributions among various methods as compared to field data.

	Left Chnl	Right Chnl
Field	49.5%	50.5%
Baseline	52.7%	47.3%
Blocked	16.6%	83.4%
Rough - 0.1	48.4%	51.6%
Rough - 0.2	43.1%	56.9%
Rough - 1.0	31.5%	68.5%
C_d - 10	48.6%	51.4%
C_d - 25	45.8%	54.2%

Inundation Extent and Velocity Distribution

Another way to verify model results is to qualitatively observe trends around the structures. Resulting inundation extent and velocity distributions of three of the employed verification methods were visually compared against field observations. An example of one such area is shown in Figure 11, which is at the downstream-most LWS in the left channel just before the channels come together (station 475 on Figure 10). The inundation extent is well represented for all methods except for fully block obstructions, which seems to overly constrict the channel at this project site. All three methods underestimate velocity, both the magnitude and the extent of the high velocity zones. Velocity is often used to inform the design of LWS; therefore, care should be taken when pulling absolute values from a 2D model. The pattern most like the field observations appears to be when using drag force. While the magnitudes are different, this could likely be overcome by adjusting the drag coefficient. The roughness only methodology also has a similar distribution pattern as to what is observed in the field and with closer magnitudes, but the channel velocities upstream of the LWS are noticeably lower. Whichever method is applied, practitioners should conduct a sensitivity analysis to ensure the full range of results are acceptable.

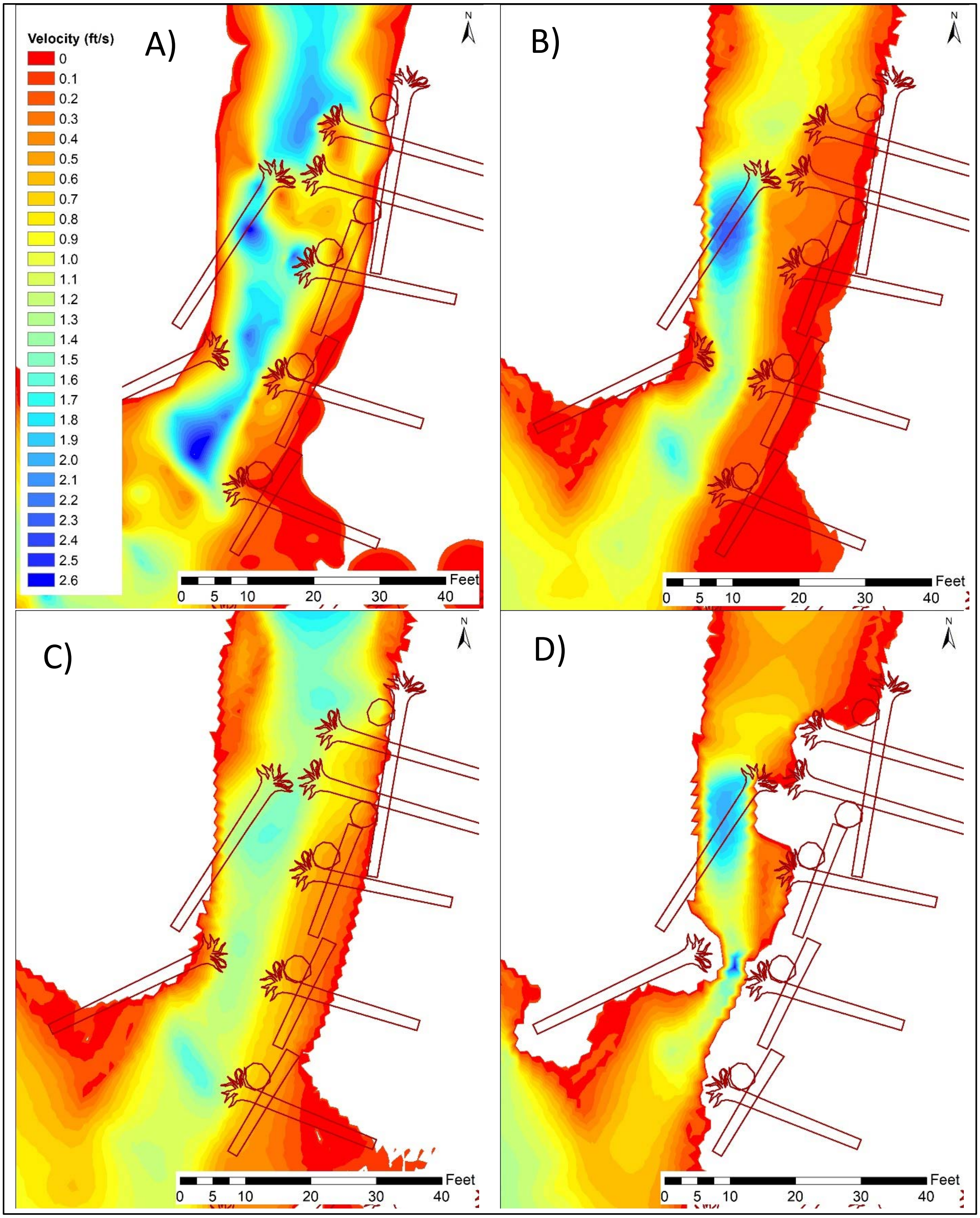

Figure 11. Velocity distributions around an LWS comparing A) field observations, B) roughness only (n = 1.0), C) drag coefficient (C_d = 25), and D) full blocked obstruction.

Conclusion

The overall goal of this research was to evaluate the representation effectiveness of modeling LWS with a two-dimensional hydraulics model to aid in the design of these features as well as gain a better understanding of the model limitations and uncertainty. The intent behind using a two-dimensional model was to make the results applicable to large scale restoration projects with potentially hundreds of wood installations. Therefore, each structure was represented through idealized simplifications of actual geometries. A sensitivity analysis of various representation techniques was utilized to gain a better understanding of the range of hydraulics impact that can be registered by varying different model input parameters. The deemed most promising of these modeling methods were then used to evaluate the representation effectiveness on a series of field installations by comparing water surface elevations and discharge against field measured data.

It was determined through field verification that more than one representation technique can be used to hydraulically represent structure effects reasonably well; a single preferred method did not surface, at least with respect to absolute accuracy. Ultimately, each method has calibration parameter(s) that can be adjusted to best match field observations, but some of these adjustments adversely impact certain hydraulic variables and some methods result in more representative flow and distribution patterns than others. Whichever method is applied, practitioners are encouraged to perform a sensitivity analysis to better understand the full range of effect LWS may have on project conditions.

It is important to know the projects goals and objectives when selecting a representation technique to employ. Another valid factor when selecting a representation technique is ease of model implementation. A greater confidence in model results forecasting structure effects for whichever method is chosen was gained with this research that ultimately leads to better design and consequently greater structure stability along with a clearer picture of the project benefits that are being sought.

Next Steps

Due to field data availability limitations, this research focused on only one river and only one project site. It is not yet known if the parameterization values used are applicable to other types of LWS installations on other types of river systems. Recommended next steps would be to apply what was learned to other types of structures on other river systems.

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Appendix A – Sensitivity Analysis Results

Scenario 1	Pt No.	Pt Desc	Water Depth (ft)	Velocity Magnitude (ft/s)	Froude	Shear Stress (lb/ft^2)
Baseline	1	Chnl in between	4.5	3.4	0.3	0.2
Baseline	2	LWM 1	4.6	4.2	0.3	0.3
Baseline	3	LWM 2	3.1	5.2	0.5	0.5
Baseline	4	Chnl adj to LWM 1	4.5	4.0	0.3	0.2
Baseline	5	Chnl adj to LWM 2	3.8	2.6	0.2	0.1
Baseline	6	Chnl upstream	3.7	6.4	0.6	0.7
Baseline	7	Chnl downstream	4.4	6.1	0.5	0.6

Scenarios 2-5	Pt No.	Pt Desc	Water Depth (ft)	Velocity Magnitude (ft/s)	Froude	Shear Stress (lb/ft^2)	% Change from Baseline Water Depth	% Change from Baseline Vel. Mag	% Change from Baseline Shear Stress
Blocked	1	Chnl in between	5.1	1.4	0.1	0.0	12%	-60%	-85%
Blocked	2	LWM 1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Blocked	3	LWM 2	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Blocked	4	Chnl adj to LWM 1	5.6	6.3	0.5	0.6	25%	60%	138%
Blocked	5	Chnl adj to LWM 2	4.4	5.5	0.5	0.5	17%	108%	310%
Blocked	6	Chnl upstream	5.3	4.3	0.3	0.3	42%	-33%	-60%
Blocked	7	Chnl downstream	4.6	6.3	0.5	0.6	5%	4%	7%

Scenarios 6-9	Pt No.	Pt Desc	Water Depth (ft)	Velocity Magnitude (ft/s)	Froude	Shear Stress (lb/ft^2)	% Change from Baseline Water Depth	% Change from Baseline Vel. Mag	% Change from Baseline Shear Stress
Partial Obstructions n = 0.03	1	Chnl in between	4.7	2.4	0.2	0.1	5%	-30%	-52%
Partial Obstructions n = 0.03	2	LWM 1	4.8	2.2	0.2	0.1	3%	-49%	-74%
Partial Obstructions n = 0.03	3	LWM 2	2.9	1.0	0.1	0.0	-6%	-80%	-96%
Partial Obstructions n = 0.03	4	Chnl adj to LWM 1	4.8	5.5	0.4	0.5	6%	39%	88%
Partial Obstructions n = 0.03	5	Chnl adj to LWM 2	4.0	4.1	0.4	0.3	5%	56%	141%
Partial Obstructions n = 0.03	6	Chnl upstream	4.3	5.4	0.5	0.5	16%	-15%	-32%
Partial Obstructions n = 0.03	7	Chnl downstream	4.3	5.9	0.5	0.6	0%	-2%	-4%
Partial Obstructions n = 0.1	1	Chnl in between	4.9	1.6	0.1	0.0	8%	-53%	-78%
Partial Obstructions n = 0.1	2	LWM 1	5.0	1.6	0.1	0.4	9%	-63%	47%
Partial Obstructions n = 0.1	3	LWM 2	3.1	1.0	0.1	0.2	1%	-81%	-60%
Partial Obstructions n = 0.1	4	Chnl adj to LWM 1	5.0	5.6	0.4	0.5	10%	42%	95%
Partial Obstructions n = 0.1	5	Chnl adj to LWM 2	4.1	4.5	0.4	0.3	9%	70%	182%
Partial Obstructions n = 0.1	6	Chnl upstream	4.6	5.0	0.4	0.4	23%	-21%	-42%
Partial Obstructions n = 0.1	7	Chnl downstream	4.3	6.0	0.5	0.6	-1%	0%	-1%
Partial Obstructions n = 0.2	1	Chnl in between	5.1	1.0	0.1	0.0	13%	-70%	-91%
Partial Obstructions n = 0.2	2	LWM 1	5.3	1.3	0.1	1.0	15%	-70%	289%
Partial Obstructions n = 0.2	3	LWM 2	3.3	1.1	0.1	0.9	6%	-79%	87%
Partial Obstructions n = 0.2	4	Chnl adj to LWM 1	5.2	5.9	0.5	0.5	15%	49%	112%
Partial Obstructions n = 0.2	5	Chnl adj to LWM 2	4.3	4.9	0.4	0.4	14%	85%	228%
Partial Obstructions n = 0.2	6	Chnl upstream	4.9	4.6	0.4	0.3	33%	-28%	-52%
Partial Obstructions n = 0.2	7	Chnl downstream	4.3	6.1	0.5	0.6	-1%	1%	3%
Partial Obstructions n = 1.0	1	Chnl in between	5.6	0.2	0.0	0.0	24%	-95%	-100%
Partial Obstructions n = 1.0	2	LWM 1	5.8	0.3	0.0	1.8	26%	-92%	555%
Partial Obstructions n = 1.0	3	LWM 2	3.5	0.5	0.1	5.0	14%	-90%	938%
Partial Obstructions n = 1.0	4	Chnl adj to LWM 1	5.6	6.5	0.5	0.6	25%	65%	152%
Partial Obstructions n = 1.0	5	Chnl adj to LWM 2	4.8	5.6	0.5	0.5	26%	112%	314%
Partial Obstructions n = 1.0	6	Chnl upstream	5.7	3.9	0.3	0.2	54%	-38%	-67%
Partial Obstructions n = 1.0	7	Chnl downstream	4.3	6.5	0.6	0.7	-2%	7%	15%

Scenarios 10-12	Pt No.	Pt Desc	Water Depth (ft)	Velocity Magnitude (ft/s)	Froude	Shear Stress (lb/ft^2)	% Change from Baseline Water Depth	% Change from Baseline Vel. Mag	% Change from Baseline Shear Stress
Unblocked n = 0.1	1	Chnl in between	4.8	2.6	0.2	0.1	6%	-26%	-46%
Unblocked n = 0.1	2	LWM 1	5.0	3.0	0.2	1.5	8%	-28%	462%
Unblocked n = 0.1	3	LWM 2	3.3	3.4	0.3	2.2	5%	-35%	356%
Unblocked n = 0.1	4	Chnl adj to LWM 1	4.9	3.7	0.3	0.2	9%	-6%	-14%
Unblocked n = 0.1	5	Chnl adj to LWM 2	4.0	3.4	0.3	0.2	4%	28%	62%
Unblocked n = 0.1	6	Chnl upstream	4.0	5.9	0.5	0.6	8%	-7%	-16%
Unblocked n = 0.1	7	Chnl downstream	4.6	5.5	0.5	0.5	7%	-8%	-18%
Unblocked n = 0.2	1	Chnl in between	5.0	1.6	0.1	0.0	11%	-53%	-78%
Unblocked n = 0.2	2	LWM 1	5.2	2.0	0.2	2.7	14%	-52%	890%
Unblocked n = 0.2	3	LWM 2	3.4	2.2	0.2	3.7	10%	-58%	669%
Unblocked n = 0.2	4	Chnl adj to LWM 1	5.2	4.3	0.3	0.3	16%	10%	15%
Unblocked n = 0.2	5	Chnl adj to LWM 2	4.2	4.2	0.4	0.3	10%	58%	143%
Unblocked n = 0.2	6	Chnl upstream	4.4	5.3	0.4	0.4	19%	-17%	-35%
Unblocked n = 0.2	7	Chnl downstream	4.6	5.4	0.4	0.5	6%	-10%	-21%
Unblocked n = 1.0	1	Chnl in between	5.5	0.3	0.0	0.0	21%	-91%	-99%
Unblocked n = 1.0	2	LWM 1	5.8	0.6	0.0	5.6	27%	-86%	1967%
Unblocked n = 1.0	3	LWM 2	3.7	0.7	0.1	8.0	18%	-87%	1567%
Unblocked n = 1.0	4	Chnl adj to LWM 1	5.7	5.7	0.4	0.5	28%	45%	93%
Unblocked n = 1.0	5	Chnl adj to LWM 2	4.6	5.3	0.4	0.4	22%	103%	286%
Unblocked n = 1.0	6	Chnl upstream	5.3	4.3	0.3	0.3	42%	-32%	-59%
Unblocked n = 1.0	7	Chnl downstream	4.5	5.9	0.5	0.5	4%	-2%	-5%

Scenarios 13-15	Pt No.	Pt Desc	Water Depth (ft)	Velocity Magnitude (ft/s)	Froude	Shear Stress (lb/ft^2)	% Change from Baseline Water Depth	% Change from Baseline Vel. Mag	% Change from Baseline Shear Stress
Drag C_D = 1.3	1	Chnl in between	4.7	2.7	0.2	0.1	4%	-21%	-38%
Drag C_D = 1.3	2	LWM 1	4.8	3.1	0.3	0.1	5%	-25%	-45%
Drag C_D = 1.3	3	LWM 2	3.3	3.9	0.4	0.3	5%	-26%	-47%
Drag C_D = 1.3	4	Chnl adj to LWM 1	4.7	4.1	0.3	0.3	5%	3%	5%
Drag C_D = 1.3	5	Chnl adj to LWM 2	4.0	3.2	0.3	0.2	4%	22%	46%
Drag C_D = 1.3	6	Chnl upstream	4.0	5.9	0.5	0.6	7%	-7%	-16%
Drag C_D = 1.3	7	Chnl downstream	4.3	5.9	0.5	0.5	0%	-2%	-5%
Drag C_D = 10	1	Chnl in between	5.0	1.4	0.1	0.0	9%	-60%	-84%
Drag C_D = 10	2	LWM 1	5.2	1.7	0.1	0.0	13%	-59%	-84%
Drag C_D = 10	3	LWM 2	3.5	2.2	0.2	0.1	11%	-58%	-83%
Drag C_D = 10	4	Chnl adj to LWM 1	5.1	4.8	0.4	0.3	13%	22%	42%
Drag C_D = 10	5	Chnl adj to LWM 2	4.2	4.2	0.4	0.3	11%	61%	149%
Drag C_D = 10	6	Chnl upstream	4.5	5.1	0.4	0.4	20%	-19%	-38%
Drag C_D = 10	7	Chnl downstream	4.3	6.0	0.5	0.6	-1%	-2%	-3%
Drag C_D = 25	1	Chnl in between	5.1	0.7	0.1	0.0	12%	-79%	-96%
Drag C_D = 25	2	LWM 1	5.3	1.2	0.1	0.0	16%	-71%	-92%
Drag C_D = 25	3	LWM 2	3.5	1.6	0.2	0.0	14%	-69%	-91%
Drag C_D = 25	4	Chnl adj to LWM 1	5.2	5.2	0.4	0.4	16%	32%	66%
Drag C_D = 25	5	Chnl adj to LWM 2	4.3	4.6	0.4	0.3	14%	76%	195%
Drag C_D = 25	6	Chnl upstream	4.7	4.9	0.4	0.4	27%	-23%	-46%
Drag C_D = 25	7	Chnl downstream	4.3	6.0	0.5	0.6	-1%	0%	0%