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

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Abstract

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 safety factors resulting in better, faster, cheaper installations as well as ensure feature effectiveness, stability, and longevity.

The Bureau of Reclamation has 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. Applying the results of this sensitivity analysis to a field data set the best overall methodology was selected and it was determined just how applicable two-dimensional hydraulics modeling can be in representing large wood structures.

Introduction

Large Wood Structures (LWS) are widely used in stream and watershed restoration projects due to the many ecological benefits it offers. 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, 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. 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. 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 validation between what the model outputs and what is observed in the field is still being resolved through collaborative research. 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 conventional than ever before and is far superior to one-dimensional models in examining large wood effects. The advantage of using two-dimensional models in habitat restoration studies 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 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 through a compromise between solution accuracy and computing demand.

Study Approach

Reclamation partnered with the Sonoma County Water Agency 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 applied the results of the sensitivity analysis that yielded the most reasonable foreseen modeling approaches to a field data set to determine the best overall methodology and see how applicable two-dimensional hydraulics modeling can be in representing large wood structure effects.

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 known 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.

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 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).

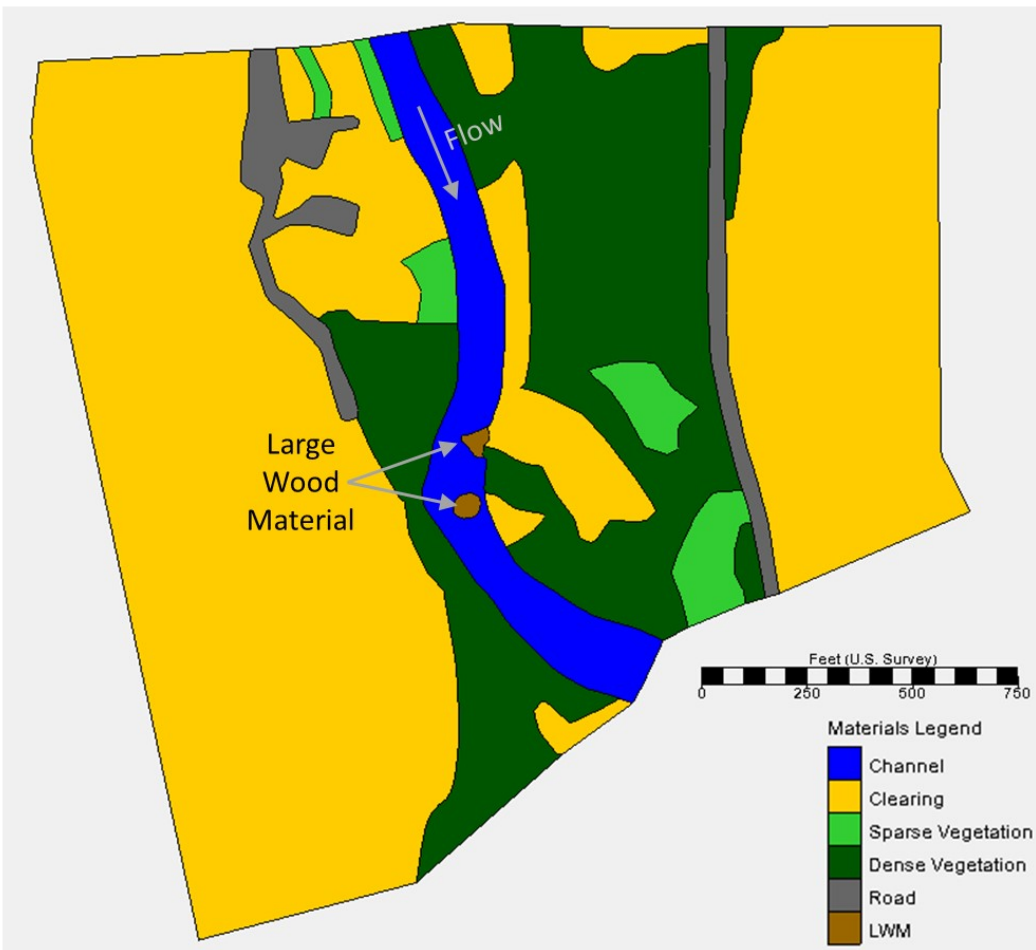

Figure 1. Sensitivity analysis model domain and material delineations.

Modeling Methodology: For the sensitivity analysis, large wood structures were modeled utilizing four methods: adding obstructions (fully or partially blocked), increasing the Manning's roughness value (n), increasing the drag coefficient (C_D), or a combination. A total of 15 model scenarios were executed, including baseline conditions, Table 1.

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	Increase drag coefficient	C_D = 1.3
7	Increase drag coefficient	C_D = 10
8	Increase drag coefficient	C_D = 25
9	Increase roughness	n = 0.1
10	Increase roughness	n = 0.2
11	Increase roughness	n = 1.0
12	Partial obstruction	n = 0.03
13	Partial obstruction + increase roughness	n = 0.1
14	Partial obstruction + increase roughness	n = 0.2
15	Partial obstruction + increase roughness	n = 1.0

Fully blocked obstructions were created by raising the model mesh elevations to the design elevation of the top of the large wood structure. 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 prove to produce overly conservative results. 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 a LWS as a partially blocked obstruction through three, 10 ft-by-5 ft elevated rectangles spaced 14 ft apart (center-to-center), was another employed method to try and better simulate the permeable nature of LWS.

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).

Finally, increasing the drag coefficient within the LWS footprint was another tested approach. 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's important to note that commonly cited drag coefficients (e.g. Engineering ToolBox, 2004) are not applicable for 2D depth-averaged processes that are being modeled; the drag coefficient was really used as a calibration parameter when used for representing LWS.

Model response to each method was evaluated based on changes from baseline conditions for water depth, velocity magnitude, and shear stress, which were evaluated through monitoring points at seven locations (Figure 2).

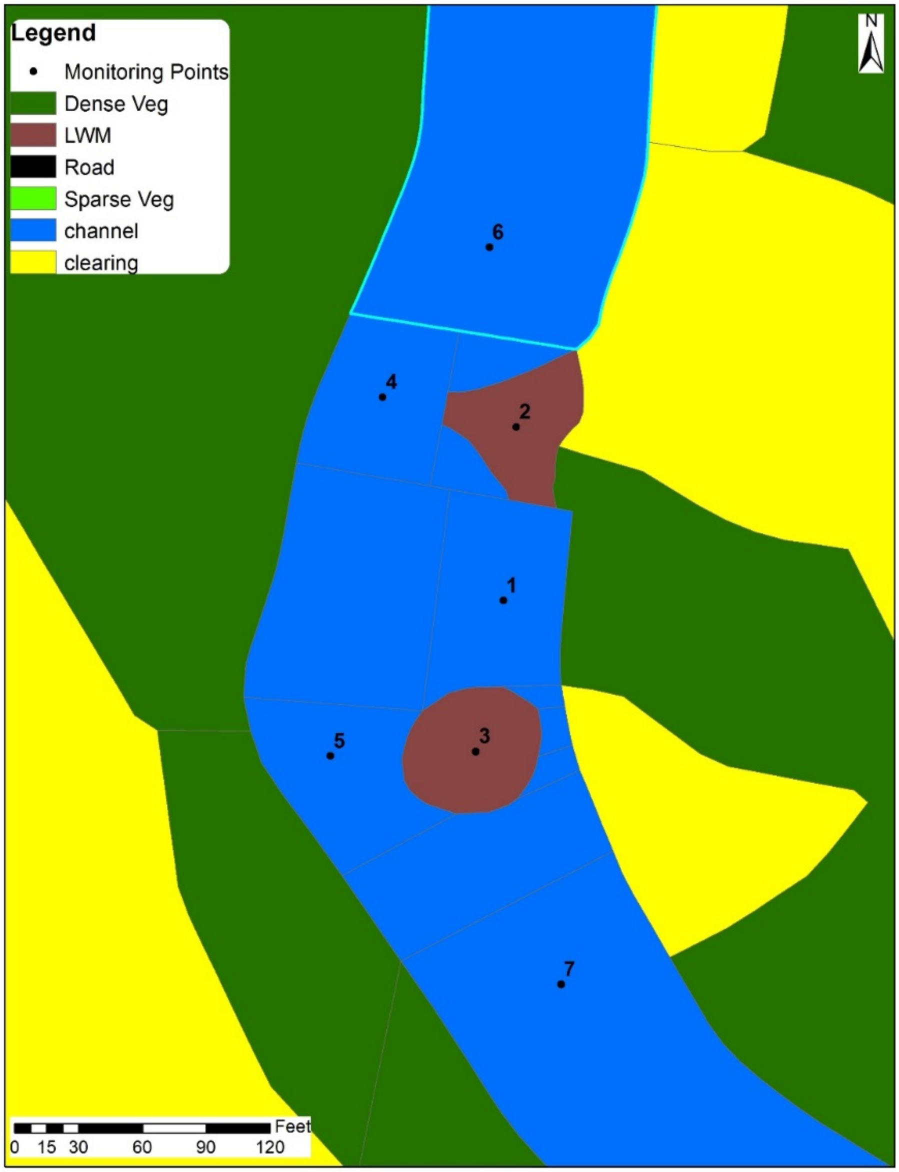

Figure 2. Sensitivity analysis model response evaluation areas.

Sensitivity Analysis Results: Hydraulically, LWS's act as large roughness elements that provide a scale-dependent 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. Baseline conditions, in which structures were not represented, established a control for the sensitivity analysis.

The fully blocked obstructions were not overtopped during the evaluated flow event. Therefore, the cells with varying roughness values were not activated and no differences were observed amongst scenarios 2 through 5. Full 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 likely 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 appropriate trends in flow depth and velocity; however, shear stress is dependent on the roughness value and do not yield realistic results when using artificially high roughness values and should be cautioned against using in design. Three different roughness values were evaluated, and while the trends were consistent throughout, the location most influenced by the change in roughness depended on its value.

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 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.

Phase II – Field Verification

The methods that yielded what were deemed as being the most realistic results from the sensitivity analysis are being 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. The field verification phase of the research is still ongoing.

Site Selection: The field sites being utilized for effectiveness modeling are located on Dry Creek below Lake Sonoma near Healdsburg, California. Numerous wood installations on three distinct project sites, all on the order of 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, depth, water surface elevation, and velocity measurements using a combination of total station, an unmanned aircraft system, and velocity flow meter mounted on a wading rod.

Methodology Verification: The tested modeling methodologies are currently being utilized to see how closely the model can represent what was measured in the field. Field data was utilized to calibrate a 'baseline' conditions model by modifying the channel roughness value

(Manning's n) until the observed water surface elevations were matched in a part of the project reach that was deemed unaffected by the presence of LWS. The various modeling methodologies were then employed to the baseline conditions and validation was performed by spatially comparing the field measured discharge flux and water depths to the modeled values. Given the sporadic and instantaneous nature of velocity, this data was only qualitatively used, ensuring consistent trends between the observed and predicted values were being represented.

Conclusion

The overall goal of this research is 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 modeling methodologies was utilized to gain a better understanding of the range of hydraulics impact that can be registered by varying different model input parameters. These modeling methodologies are currently being used to evaluate the representation effectiveness on a series of field installations; this phase of research is still in progress. A preferred method, at least with respect to absolute accuracy, may not surface from this effort considering each method will be individually calibrated to field data. However, it is hopeful that a greater confidence in model results forecasting structure effects for whichever method is chosen will be gained that ultimately leads to better design and consequently greater structure stability as well as a clearer picture of the particular project benefits that are being sought in the goals and objectives.

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