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Integrating Large Wood Jams into Hydraulic Models: Evaluating a Porous Plate Modeling Method

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Research Impact Statement: Hydraulic models are error-prone where rivers interact with large wood jams. Our method for representing wood jams improves hydraulic model accuracy and ecohydraulic analysis.

ABSTRACT: Large wood (LW) jams are key riverine habitat features that affect hydraulic processes and aquatic habitat. The hydraulic influence of LW jams is poorly understood due to the complexity of fluid dynamics around irregular, porous structures. Here we validated a method for two-dimensional hydraulic modeling of porous LW jams using the open-source modeling software Delft3D-FLOW. We sampled 19 LW jams at three reaches across the Columbia River Basin in the United States. We used computer-generated porous plates to represent LW jams in the modeling software and calibrated our modeling method by comparing model outputs to measured depths and velocities at validation points. We found that modeling outputs are error-prone when LW jams are not represented. By representing LW jams as porous plates we reduced average velocity root mean square error (RMSE) values (i.e., improved model accuracy) by 42.8% and reduced average depth RMSE values by 5.2%. These differences impacted habitat suitability index modeling. We found a 15.1% increase in weighted useable area for juvenile steelhead at one test site when LW jams were simulated vs. when they were ignored. We investigated patterns in average RMSE improvements with varying jam size, bankfull obstruction, porosity, and structure type, and river complexity. We also identified research gaps related to field estimation of LW jam porosity and porous structure modeling methods.

(KEYWORDS: rivers/streams; fluvial processes; 2D simulations; field measurements; large wood jam; hydraulic modeling; fish habitat suitability; river restoration.)

INTRODUCTION

Large wood (LW) jams are key riverine habitat features that impact hydraulic processes, overbank flood stage, geomorphology, and forested stream ecosystems (Abbe and Montgomery 1996; e.g., Abbe, Brooks, et al. 2003; Bureau of Reclamation and U.S. Army Engineer Research and Development Center 2016; Wohl 2017). For example, LW diversifies water flow characteristics while decreasing average magnitude of flow velocity (Shields and Gippel 1995; Hafs et al. 2014), impounds water which causes increased flooding during high flow events (Le Lay et al. 2013), drives the formation of multi-thread channel reaches (Abbe and Montgomery 2003; Polvi and Wohl 2013), stabilizes channel migration (Booth et al. 1996; Abbe and Montgomery 2003; Beechie et al. 2010), improves habitat for fish and macroinvertebrates (Shirvell 1990; Roni and Quinn 2001; Lester and Boulton 2008; Allen and Smith 2012), and promotes the development of complex habitat features by increasing pool frequency, channel length, and instream cover (Montgomery et al. 1995; Buffington and Montgomery 1999; Manga and

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Kirchner 2000; Abbe and Brooks 2011). LW jams are complex three-dimensional (3D) structures with a wide range of interstitial complexity (e.g., porosity) and hydraulic effects that are unique in fluvial systems. The number, size, and spatial arrangement of LW pieces in a jam, as well as the porosity of the jam as a whole, all affect the jam's hydraulic influence (Manners et al. 2007). The overall impact of LW jams on river systems has changed as human activities have depleted LW resources in many rivers worldwide (Gippel et al. 1996; Abbe et al. 2002; Abbe, Carrasquero, et al. 2003; Wohl 2014). Now LW jams are commonly installed as a part of habitat restoration projects (Hilderbrand et al. 1998; Abbe et al. 2002; e.g., Abbe, Brooks, et al. 2003; Katz et al. 2007; Manners et al. 2007; Beechie et al. 2010; Bureau of Reclamation and U.S. Army Engineer Research and Development Center 2016). In river basins that have undergone reforestation, which are common in Europe (Liébault and Piégay 2002), increased natural development of LW jams can intensify overbank flooding and make hazard predictions more uncertain (Ruiz-Villanueva, Díez-Herrero, et al. 2014). However, strategic reforestation and LW jam placement at the watershed or subwatershed scale can also mitigate flood risk in target areas (Dixon 2013; Dixon et al. 2016). Two-dimensional (2D) hydraulic modeling is used to design and assess LW jams (Bureau of Reclamation and U.S. Army Engineer Research and Development Center 2016), to document changes in fish habitat quality and quantity (Wheaton et al. 2017), to simulate LW transport through river systems (Ruiz-Villanueva, Bladé, et al. 2014; Persi et al. 2019) and to evaluate flood risks (Jain et al. 2018). However, many hydraulic modeling efforts either disregard the presence of jams or represent jams as solid, nonporous structures (Manners et al. 2007; Allen and Smith 2012; Ruiz-Villanueva, Díez-Herrero, et al. 2014; Tullos and Walter 2015). In reality, most LW jams are complex, porous structures that can contain thousands of individual LW pieces and provide valuable microhabitats (O'Neal 2000; Abbe and Montgomery 2003; Manners et al. 2007; Tullos and Walter 2015). For example, Tullos and Walter (2015) found that proximity to wood was a better indicator of quality microhabitat than any hydraulic measure of the flow field for juvenile coho salmon (*Oncorhynchus kisutch*) in cold, low flow conditions.

The specific nature of the hydraulic influence of LW jams is still poorly understood due to the complexity of fluid dynamics around irregular, porous structures (Lai and Bandrowski 2014; Bureau of Reclamation and U.S. Army Engineer Research and Development Center 2016). Several studies have investigated the hydraulic effects of LW. Manners et al. (2007) found that the level of jam porosity influences water velocities upstream, alongside, and downstream of the jam, and that the assumption of nonporosity in jam modeling can result in a 10%–20% overestimation of drag force. Potentially contradictory results from Shields and Alonso (2012) show that drag coefficients on LW pieces decline as branch density increases, whereas Hygelund and Manga (2003) found that the experimental addition of leafless branches to LW pieces does not increase drag. Gippel et al. (1996) reported that adjacent pieces of debris in river flow have complex interactions that can result in counterintuitive hydraulic effects. Schalko et al. (2018) used flume experiments to study the backwater effect of LW jams, finding that backwater rise depends mainly on the approach flow and LW jam porosity, the latter of which was significantly influenced by the percentage of fine organic material. Hartlieb (2017) reported similar findings, but noted that backwater effect can vary significantly between different test runs with identical test conditions, due to the randomness of debris jam development. Clearly, additional research is warranted. Reach scale hydraulic models that ignore LW jams have been shown to successfully match stream hydraulics in areas without instream LW when surveyed velocities and depths are compared to modeled velocities and depths at validation points, but there is concern that model outputs are error-prone where LW jams interact with stream hydraulics (Nahorniak et al. 2018).

Flood prediction and ecohydraulic models (including aquatic habitat suitability modeling) depend on accurate velocity and depth inputs derived from hydraulic modeling to provide relevant results (Liu and Ramirez 2013; Dixon et al. 2016; Jain et al. 2018). The potential for hydraulic models to guide assessment of habitat, restoration actions, and flood risks is limited by the lack of tested methods for representing porous LW jams in 2D or 3D models. Model validation using field data is crucial (Constantinescu et al. 2016). The goal of this study was to determine whether the use of porous plate LW jam representations in the open-source software Delft3D-FLOW (Deltares 2014) improves 2D hydraulic model outputs. The porous plate feature in Delft3D-FLOW allows us to simulate resistance to flow throughout the water column in hydraulic models. We use a case analysis of Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss*) habitat suitability in the Columbia River Basin, Washington to demonstrate the impact of the exclusion of LW jams on ecohydraulic modeling results. We hypothesize that the use of porous plate LW jam representations will produce more accurate hydraulic model outputs for water velocities and depths around LW jams, compared to model outputs where LW jams were not represented. If so, this will improve hazard planning, restoration design, and habitat evaluation.

MATERIALS AND METHODS

Field Methods

The Bonneville Power Administration's Columbia Habitat Monitoring Program (CHaMP) and Action Effectiveness Monitoring Program (AEM) generate reach level data for hundreds of reaches across the Columbia River Basin (Wheaton et al. 2017). We selected three existing AEM study sites for LW jam modeling: Tucannon River Project Area 24, Catherine Creek Southern Cross, and Twisp River Floodplain Phase 1 (Figure 1, for additional information see https://www.aemonitoring.org/). We selected these sites because they each have multiple LW jams and detailed AEM bathymetric survey data for hydraulic modeling. Engineered LW jams were installed at all three sites in 2015 as a part of habitat restoration actions. We were unable to select sites that hosted the entire spectrum of LW jam shapes, sizes, and porosities, since our site selection process was limited to AEM-surveyed restoration projects with detailed bathymetric data. Due to modeling limitations, we limited validation to only jams that extended above the water surface during high flow surveys and did not sample any that clearly occupied only a portion of the water column. The LW jams present at the study sites included bar apex, meander, and deflector jams. Bar apex jams are LW structures in the middle of the channel at the upstream end of islands or bars, and that contribute to island or bar formation and maintenance. Meander jams are LW structures on the outside of meander bends that accumulate fluvial wood, create and maintain scour pools, and affect bank erosion. Deflector jams are LW structures located throughout the channel that force flow to change directions through direct impact or deflection, often creating diverse physical conditions and trapping additional debris (Bureau of Reclamation and U.S. Army Engineer Research and Development Center 2016).

We used a total station to survey periys of LW jams and visually estimated jam porosities for 19 qualifying jams at three study sites during low flow conditions in summer 2016. Qualifying LW jams were defined as stable, unified LW accumulations of at least three key or racked members (Abbe and Montgomery 2003) that interact with stream hydraulics at bankfull flows as a relatively uniform porous structure. We collected up to 10 topographic points around the immediate edge of each jam to record an accurate perimeter polygon. Points were collected to represent the footprint of the core porous structure, and were not collected where individual pieces of wood protruded far from the heart of the jam (Figure 2). Jam porosity was defined as the percentage volume of the 3D space occupied by the jam (based on the jam extent defined by the surveyed perimeter footprint) that is *not* occupied by wood or other solid material. We visually estimated porosity after training in ocular estimation using visual aids, including cards designed for calibrating riparian canopy cover and substrate percentage estimates. We relied on this calibration and the following written jam descriptions (adapted from Scott et al. 2018) to guide porosity estimation to the nearest 10%:

1. Estimated porosity is from 10% to 30%: Surveyor cannot see light coming through most of the jam. Jam creates significant backwater and flow through the jam is heavily obstructed.
2. Estimated porosity is from 40% to 60%: Surveyor can see light coming through the jam, but may not be able to see through the jam in many locations. Flow is obstructed, but significant amounts of water can still pass through the jam. Noticeable change in water surface elevation from upstream to downstream side of jam.
3. Estimated porosity is from 70% to 90%: Surveyor can see light through most parts of the jam. Water encounters resistance but can flow easily through the jam. Large voids in jam.

In April 2017, when river flows were elevated and jams were significantly engaged with the water column, we returned to each study site to collect water depth and velocity validation data (Figure 3). At each jam we noted changes in porosity, resurveyed changed perimeters, and collected a group of seven to fourteen validation points in the water within the jam's zone of visible hydraulic influence (generally within 3 m of the jam perimeter). Points were taken within the jam structure where possible. At each validation point, we measured water depth and velocity (including water speed and compass bearing corrected for declination) using a portable electromagnetic flow meter (FH950 Handheld Flow Meter, Hach Company, Loveland, Colorado) and top-setting depth rod. Velocity measurements were taken at 60% depth to get the most accurate approximation of depth-averaged velocity (Leopold et al. 1964; Finnemore and Franzini 2001; Gordon et al. 2004). Each velocity measurement was averaged over a 10 s sampling period. We georeferenced exact validation point locations using a total station. We also collected velocity and depth validation points during low flow conditions in summer 2016, but many jams were not interacting with low flow stream hydraulics (e.g., Figure 2, lower left).

After field work was completed, we combined LW jam perimeter data with AEM bathymetric surveys in ArcGIS (ESRI 2012). We processed bathymetric

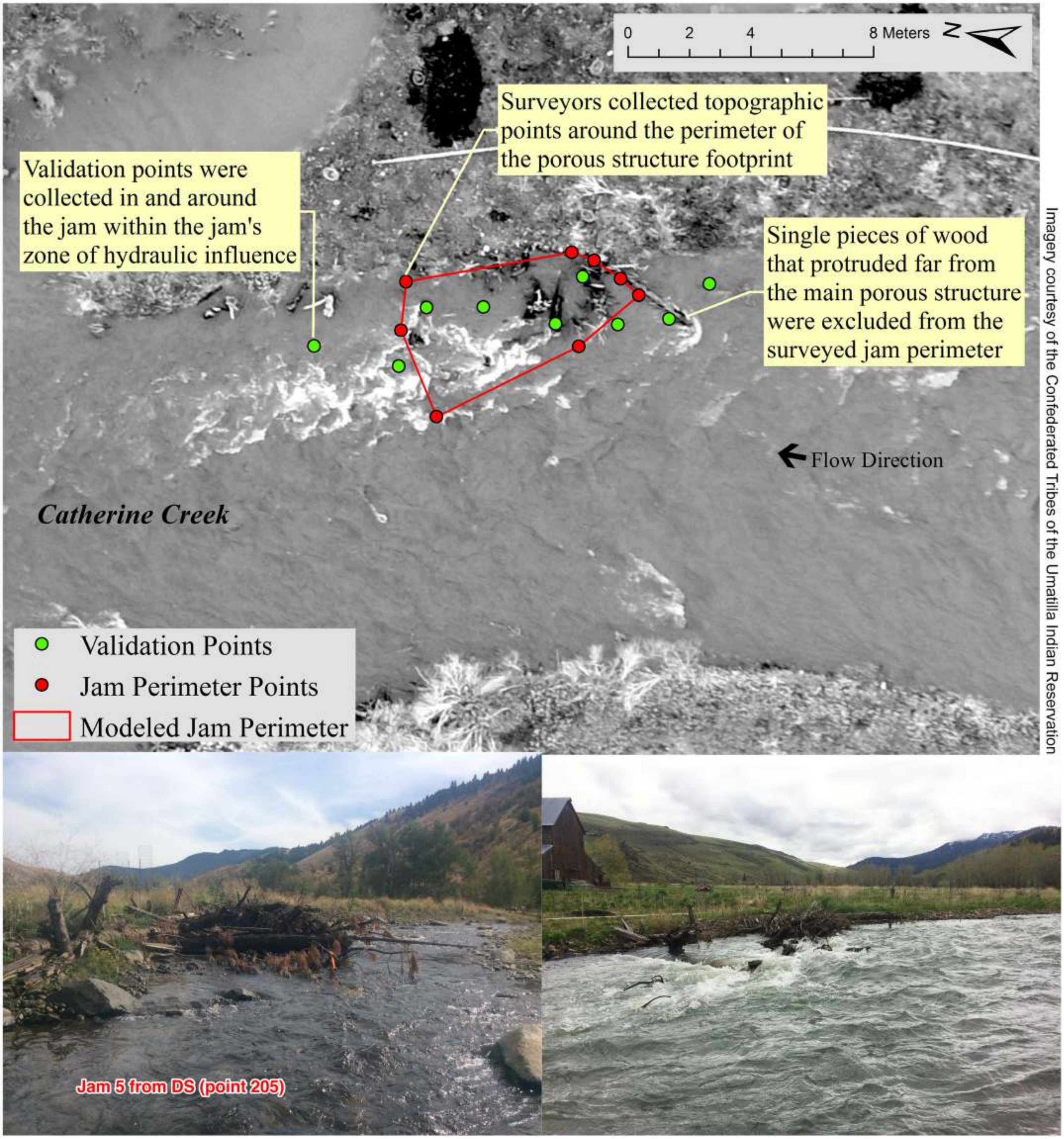
FIGURE 1. Locations of large wood (LW) jam modeling study sites in the Columbia River Basin.

surveys in preparation for modeling using the CHaMP topographic toolbar in ArcGIS 10.1 (North Arrow Research 2017), which included the creation of a triangulated irregular network and digital elevation model (DEM) using field survey points from each site. We used bathymetric surveys from summer 2016 for both the Catherine Creek and Twisp River sites, and used bathymetric surveys from summer 2017 for the Tucannon River site since it was altered by high flows in March 2017.

Modeling Methods

We used Delft3D-FLOW to complete hydraulic modeling in a 2D computational grid (Deltares 2014). We set computational grid cell size to maximize the number of grid cells without exceeding computer memory limitations, and were able to use higher grid cell densities at smaller sites; computational grid cell size was 0.3 m at the Tucannon River site, 0.4 m at the Catherine Creek site, and 0.5 m at the Twisp River site (Figure 4). The vertical dimension was not solved from the full set of fluid dynamic equations (i.e., the computational grid does not extend in the Z-axis direction), but rather the vertical velocity profile was assumed based on the depth-averaged velocity output and surface roughness. We set modeled flows to match stream discharge at the time of survey.

We used DEM at a 0.1-m grid spacing, average substrate roughness, stream discharge, and water surface elevation DEM (WSDEM) from the AEM database as inputs to compute hydraulic models for the survey sites, defining boundary conditions from the WSDEM. Delft3D-FLOW includes a feature enabling the addition of porous plates to the simulated hydraulics; we used these porous plates to represent LW jams in the hydraulic model. Porous plates are groups of points in the computational grid where resistance to flow is added to the governing equations to simulate the effect of a porous structure (Deltares



Imagery courtesy of the Confederated Tribes of the Umatilla Indian Reservation

FIGURE 2. Example of jam perimeter and validation point data collection at Catherine Creek Jam 5. Jam perimeter data were collected under low flow conditions (lower left, view from downstream), whereas validation points were collected under high flow conditions (lower right, oblique view). The aerial imagery shows Jam 5 engaged with Catherine Creek at bankfull flow, which is higher than our survey flows.

2014). We adjusted the hydraulic effect of each set of porous plates using a friction factor inversely related to the porosity of each LW jam, and used field validation data to calibrate these friction factors.

We did not model truly 3D porous structures using porous plates, but rather approximated them as infinitely tall extrusions of 2D jam footprints. Water can flow through or around these features (with increased

FIGURE 3. Collecting validation point data using a portable electromagnetic velocity meter at Catherine Creek Jam 5 under high flow conditions, April 2017.

resistance to flow at lower porosity levels), but cannot flow over these features in the hydraulic model. While this is a limitation to our hydraulic modeling capabilities, it is nonetheless consistent with the actual LW jams we modeled (i.e., porosity is relatively consistent throughout the water column and water does not fully submerge these structures under most flows).We converted field data on LW jam footprints and porosities into Delft3D-FLOW input files that specified a set of porous plate locations (i.e., jam representations) as well as a friction factors for each porous plate (i.e., jam). We approximated friction factor values as an inverse function of porosity (lower porosity results in greater resistance to flow). A friction factor input for each LW jam was created from the porosity estimate as:

$$\text{Friction Factor Input} = \alpha \times (100 - \text{Porosity}), \tag{1}$$

where α is a scalar value that was adjusted to calibrate hydraulic modeling results to measured water depth and velocity values at validation points. The linear form of the equation was assumed and is likely oversimplified, but proved useful to reasonably translate actual LW jams into digital representations. Our friction factor input equation is consistent with Manners et al. (2007), who found an inverse relationship between drag force and porosity in LW jams.

We translated the surveyed LW jam locations to porous plate locations on the computational grid (Figure 4). While Delft3D-FLOW enables specification of porous plates covering a range of grid cells, we chose to build up each porous structure as an accumulation of many "plates" that each only covered a single grid cell. This makes it easier to generate irregularly shaped footprints for each porous structure and enables variation in friction factors across the area of a porous structure (although at this point, we assigned each porous structure only a single, uniform friction factor). In addition, we assumed equal friction in X and Y grid directions within each modeled LW jam.

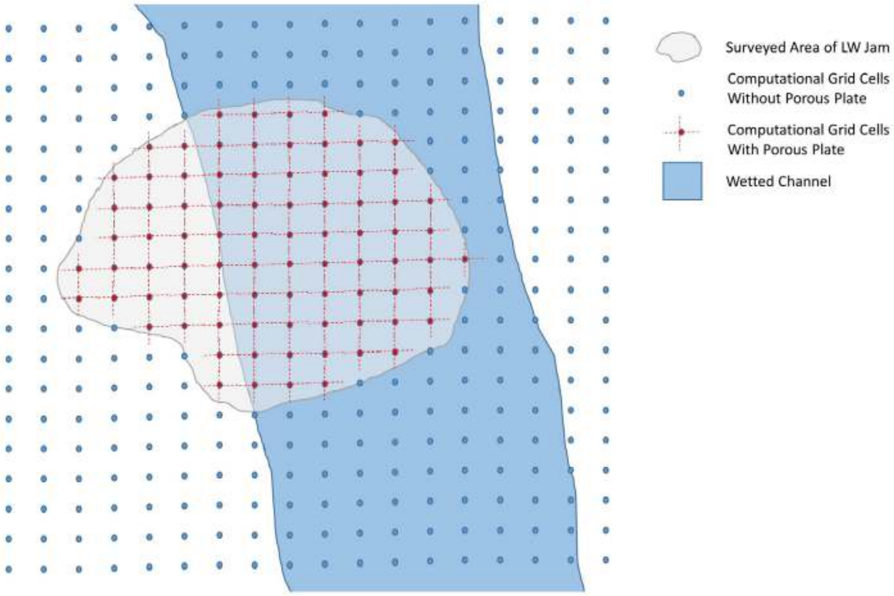


FIGURE 4. Example of a hypothetical LW jam footprint, as viewed from above, overlaid onto the hydraulic model computational grid. Grid cells onto which porous plates are assigned are shown in red. Each porous plate cell can be assigned a unique friction factor that partially allows for the transfer of mass and momentum across the porous plate. The porous plates are assumed to be infinitely tall, such that water can flow through and around, but not over, the structural representation in the hydraulic model.

We then compared hydraulic model results without porous plates and with porous plates (represented with a range of α-scaled friction factors) to the measured velocities and depths around each LW jam to assess the performance of the hydraulic models. To detect differences between modeled and measured velocities and depths, we calculated velocity and depth error at each validation point (i.e., the difference between measured results and modeled results). We separated velocity into its X and Y components to unify magnitude and direction into one variable. Next, we calculated root mean square error (RMSE) by LW jam for depth, X component of velocity, and Y component of velocity. The two velocity components of RMSE were then averaged together for each validation point.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\left(E_1^2 + E_2^2 + E_3^2 + \ldots + E_n^2\right)}, \tag{2}$$

where E is the error between measured and modeled components of velocity at a given validation point, and n is the number of errors that were included for a given LW jam (two errors were included for each validation point, one for the X component of velocity and one for the Y component of velocity).

RMSE was used as the model assessment criterion over mean absolute error (MAE) to give higher weights to larger errors. RMSE penalizes variance by giving errors with larger absolute values more weight than errors with smaller absolute values (Chai and Draxler 2014). Both RMSE and MAE are widely used in model assessment.

Aside from the inclusion of porous structures, we generated hydraulic models in this study using the default CHaMP/AEM hydraulic modeling process (Nahorniak et al. 2018). All hydraulic modeling procedures, including R code and modifications for porous plate modeling, are available in a publicly accessible repository at https://github.com/SouthForkResearch/Hydraulic-Modeling

In order to investigate how inclusion or exclusion of LW jams in hydraulic modeling impacts habitat assessment, we ran juvenile Chinook salmon and juvenile steelhead habitat suitability index (HSI) models at the Catherine Creek Southern Cross study site (which had both the most LW jams and greatest proportion of LW jam coverage compared to the other sites), using hydraulic model results with and without porous plate representation of LW jams. The HSI model assigned a suitability value, ranging from zero (poor habitat) to one (ideal habitat), to each hydraulic grid cell based on water depth and velocity habitat suitability curves developed by Raleigh et al. (1984) and Raleigh et al. (1986). We processed the HSI model using North Arrow Research's Habitat Model software (North Arrow Research 2018). We compared weighted usable area (WUA), which is a metric of habitat quantity and quality based on the multiplication of each grid cell area by its habitat suitability score (Bovee and Cochnauer 1977), for model runs with and without porous plates.

RESULTS

In total, we collected 200 velocity validation points at 19 LW jams across the three study sites, averaging about 11 validation points per jam. Of the 19 surveyed LW jams, one jam was formed through natural LW recruitment and 18 jams were engineered (though natural LW racking had occurred on some engineered jams). Surveyed jam area ranged from 6.1 to 216.3 m^2. Each jam obstructed from 11% to 73% of the bankfull channel width, and mean bankfull obstruction was 35%. No jams spanned the entire wetted channel at the time of survey. Porosity estimates ranged from 40% to 90%, and median estimated porosity of surveyed jams was 70%. We reviewed jam photographs to ensure that our porosity estimation technique appeared consistent across all three sites.

River stage ranged from approximately 30% to 80% of bankfull height at survey sites during the high flow surveys, with measured discharges of 6.67 m^3/s on Catherine Creek, 7.11 m^3/s on the Tucannon River, and 14.73 m^3/s on the Twisp River. All hydraulic models ran successfully at surveyed flow levels, producing field results for depth and velocity at all three sites and across all tested values of the friction scalar α. In Figure 5 we show an example of depth and velocity output changes between model runs at the Catherine Creek survey site. Average RMSE values across all sites for both water velocity (Table 1) and depth (Table 2) were highest in model runs without porous structure representation. Porous plate representation of LW jams improved velocity RMSE at every jam surveyed under almost all friction scalar values, and improved depth RMSE at most surveyed jams under all friction scalar values (Figure 6). A low (α = 0.05) friction scalar resulted in the lowest average velocity RMSE across all jams, which created a 42.8% reduction in average RMSE from the model runs with no porous structures. A 2× low (α = 0.025) friction scalar resulted in the lowest average depth RMSE across all jams, which created a 5.7% reduction in average RMSE from the model runs with no porous structures. A low (α = 0.05) friction scalar resulted in the greatest combined reduction in average RMSE when considering both depth and velocity. Porous structure addition had greater average effects on velocities than on depths (Figure 5, Tables 1 and 2), which seems appropriate as almost all the surveyed LW jams were deflecting flows but not substantially creating a backwater effect. Porous plate jam representation resulted in slight average velocity and depth RMSE improvements under low flow conditions as well, but most jams were not significantly engaged with low flow stream hydraulics.

We compared average velocity and depth RMSE improvements with porous plate addition (when calibrated with the low friction scalar, $\alpha = 0.05$) for different types of jams to identify if our approach worked better for some jam types over others. We investigated RMSE improvements by jam size (footprint area), bankfull obstruction (the percent of the bankfull cross section obstructed by a jam at its widest point), porosity, and type (bar apex, deflector, or meander) (Figure 7). We tested for a Spearman's rank correlation in each of these relationships, and found that none were statistically significant ($p < 0.05$, Table 3). The best average velocity improvements were observed for jams that were 80% porous, whereas the best average depth improvements were observed for jams that were 60% porous. Meander jams showed greater average RMSE improvements for both velocity and depth when compared to bar apex and deflector jams. However, small sample sizes in the meander and bar apex jam categories limit our ability to draw conclusions.

We also compared average velocity and depth RMSE improvements with porous plate addition (calibrated with the low friction scalar, $\alpha = 0.05$) by monitoring site. Average RMSE improvements for both velocity and depth were highest at the Catherine Creek site, followed by the Twisp River site, and then the Tucannon River site (Figure 8). All three sites showed large improvements in average velocity RMSEs with porous plate addition, but average depth RMSEs worsened slightly at the Twisp River site and worsened considerably at the Tucannon River site. River complexity differences between the three sites could be related to these results. Both the Twisp River and Tucannon River sites are very morphologically complex, with multiple islands, braided channels, and side channels in each reach. One way to measure the complexity and changing morphology of river reaches is the river complexity index (RCI), as described by Brown (2002). RCI rises with increasing reach-level sinuosity and density of bankfull channel junctions. When arranged by RCI value, the average depth and velocity RMSE improvements for each site fit a pattern: average RMSE improvements are greater as RCI decreases (Figure 9).

Porous plate representation of LW jams also affected HSI modeling, which is commonly used in the assessment of aquatic habitat and restoration actions. The addition of porous plates (calibrated with the low friction scalar, $\alpha = 0.05$) resulted in an 11.5%

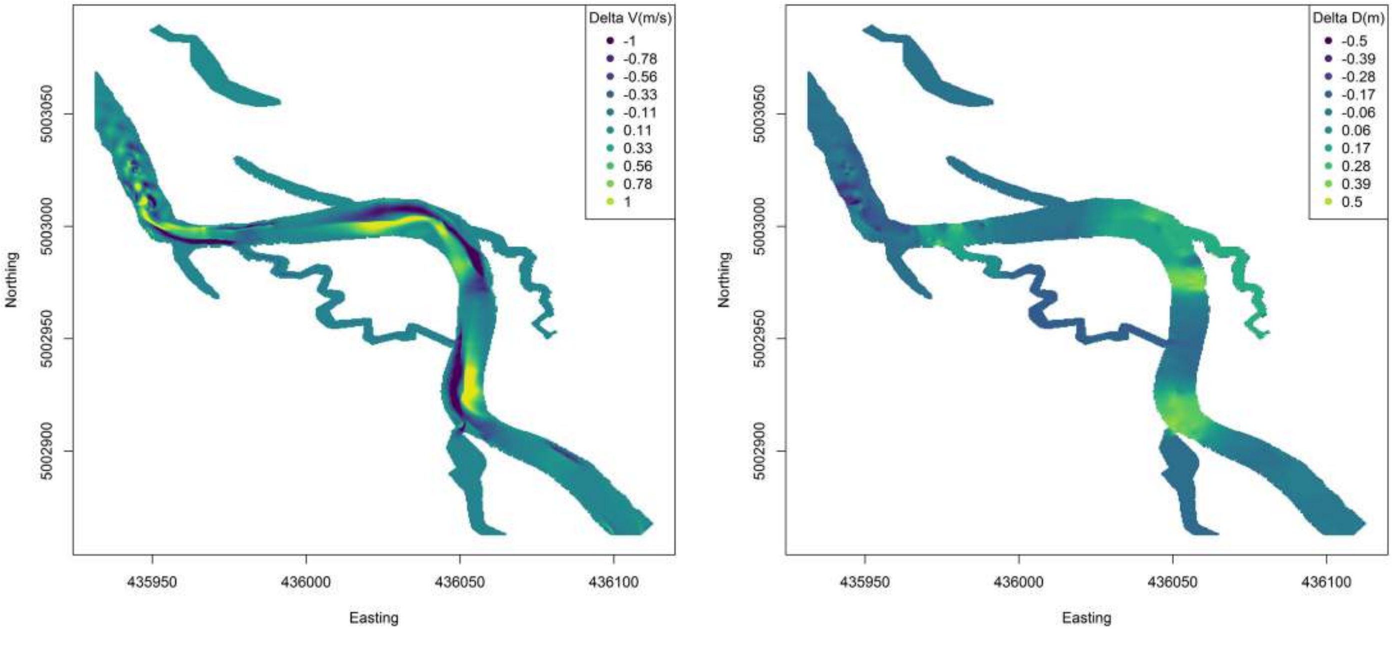


FIGURE 5. Changes in water velocities (left) and water depths (right) at the Catherine Creek survey site with the addition of porous plates calibrated with a low friction scalar ($\alpha = 0.05$). Porous plate representation of LW jams in the hydraulic model resulted in major shifts in modeled flow characteristics. Coordinates are UTM zone 11.

TABLE 1. Average velocity root mean square error (RMSE) improvements by LW Jam at high flow for various levels of the porous plate friction scalar (α).

						RMSE percent improvement with α-calibrated porous plates					
Jam ID	**Jam type**	**Jam area (m^2)**	**Bankfull obstruction (%)**	**Porosity (%)**	**RMSE: no plates (m/s)**	**4× Low friction (0.0125)**	**2× Low friction (0.025)**	**Low friction (0.05)**	**Default friction (0.1)**	**Medium friction (0.2)**	**High friction (0.4)**
Catherine 1	Meander	28.3	51	70	0.573	57.2	64.0	68.5	71.0	70.7	70.8
Catherine 2	Deflector	26.4	36	80	0.725	35.1	41.9	47.7	52.4	55.6	57.4
Catherine 3	Deflector	31.0	28	50	0.338	47.3	40.8	37.8	40.1	40.6	38.7
Catherine 4	Meander	216.3	53	90	0.378	38.3	46.9	56.2	63.8	70.0	73.5
Catherine 5	Deflector	24.4	41	70	0.357	29.5	27.4	20.6	14.5	10.6	6.8
Catherine 6	Deflector	15.5	16	80	0.381	43.7	50.7	53.7	53.9	52.7	51.1
Catherine 7	Meander	162.2	58	70	0.394	46.6	48.2	46.9	43.9	40.8	38.0
Catherine 8	Deflector	14.1	23	60	0.371	50.7	51.0	62.5	63.4	63.7	62.3
Catherine 9	Deflector	26.4	19	70	0.324	58.1	61.9	61.7	59.3	56.2	53.6
Tucannon 1	Deflector	38.6	44	90	0.397	30.0	35.1	33.8	37.4	36.0	37.3
Tucannon 2	Deflector	37.1	24	70	0.419	22.6	23.8	24.1	17.0	**−3.9**	**−14.5**
Tucannon 3	Deflector	54.3	19	90	0.446	45.0	40.7	32.6	22.6	15.5	11.0
Twisp 1	Deflector	13.2	73	50	0.405	3.3	4.2	5.1	5.7	6.2	6.6
Twisp 2	Deflector	10.7	48	40	0.420	37.5	42.3	44.4	44.2	42.4	40.0
Twisp 3	Deflector	6.1	44	50	0.295	26.5	30.5	32.2	32.0	30.7	28.8
Twisp 4	Bar apex	29.9	31	80	0.340	30.9	40.9	45.9	44.3	39.2	33.6
Twisp 5	Deflector	9.5	11	60	0.322	19.7	27.6	33.2	35.4	35.1	33.7
Twisp 6	Deflector	12.7	17	60	0.388	50.2	47.2	41.2	36.4	32.5	27.1
Twisp 7	Deflector	20.2	31	60	0.429	51.9	55.9	51.7	42.0	31.9	23.2
Average RMSE across all jams					0.405	0.249	0.236	0.232	0.235	0.246	0.256
RMSE percent improvement across all jams						38.5%	41.7%	42.8%	41.9%	39.3%	37.0%

Note: RMSE degradations are bolded. The low friction scalar (α = 0.05) offered the highest average RMSE improvements.

WUA increase for juvenile Chinook and a 15.1% WUA increase for juvenile steelhead at the Catherine Creek survey site (Figure 10).

DISCUSSION

This study shows that hydraulic modeling outputs can be error-prone where porous LW jams interact with stream hydraulics. We demonstrated the impact of LW jam modeling on ecohydraulic analyses. Our method for representation of LW jams as porous plates in the Delft3D-FLOW hydraulic model resulted in more accurate water depth and velocity outputs when averaged across all jams for all tested values of the friction scalar α. We tentatively recommend the use of a low friction scalar (α = 0.05) for future modeling efforts using this method, since it offered the greatest combined average reduction in velocity and depth RMSE values, though further research is warranted. Using the low friction scalar, the Delft3D-FLOW friction factor input for each LW jam can be tied directly to field porosity estimates through the following equation:

$$\text{Friction Factor Input} = 0.05 \times (100 - \text{Porosity}). \quad (3)$$

This modeling method clearly produced greater improvements for some individual LW jams over others. We tested potential relationships in average velocity and depth RMSE improvements with varying jam size, bankfull obstruction, porosity, and structure type, but none were statistically significant and more work is warranted to investigate which types of jams can be most accurately modeled. Using a low friction scalar (α = 0.05), our method reduced average velocity RMSEs at all individual jams across all three survey sites (Table 1). Results for depth were more variable, with a combined average RMSE improvement across all jams and average RMSE improvements at 63.2% of individual jams (Table 2). We also found that average RMSE improvements are greater as site-level river complexity decreases. This suggests that our LW jam modeling approach may work best at morphologically simple river reaches. This is not surprising, as complex river morphologies can present challenges to hydraulic modeling even without the addition of porous plates (Nahorniak et al. 2018).

There are several limitations to this study design. Visual porosity estimation inherently introduces variability between jams and surveyors, and the porosity

TABLE 2. Average depth RMSE improvements by LW jam at high flow for various levels of the porous plate friction scalar (α).

						RMSE percent improvement with α-calibrated porous plates					
Jam ID	**Jam type**	**Jam area (m^2)**	**Bankfull obstruction (%)**	**Porosity (%)**	**RMSE: no plates (m)**	**4× Low friction (0.0125)**	**2× Low friction (0.025)**	**Low friction (0.05)**	**Default friction (0.1)**	**Medium friction (0.2)**	**High friction (0.4)**
Catherine 1	Meander	28.3	51	70	0.271	4.9	5.2	4.9	5.9	6.5	8.4
Catherine 2	Deflector	26.4	36	80	0.203	23.5	26.3	28.0	29.1	29.3	29.0
Catherine 3	Deflector	31.0	28	50	0.139	15.1	21.1	26.5	30.7	33.0	33.3
Catherine 4	Meander	216.3	53	90	0.435	6.7	7.6	8.5	9.2	9.9	10.6
Catherine 5	Deflector	24.4	41	70	0.208	18.0	18.4	16.8	13.8	9.6	5.2
Catherine 6	Deflector	15.5	16	80	0.185	**−1.2**	**−1.8**	**−2.0**	**−1.8**	**−1.2**	**−0.8**
Catherine 7	Meander	162.2	58	70	0.531	9.7	10.9	12.2	13.7	15.3	16.5
Catherine 8	Deflector	14.1	23	60	0.421	19.4	24.6	29.2	34.4	38.9	42.4
Catherine 9	Deflector	26.4	19	70	0.150	5.3	5.1	5.3	5.9	7.0	8.2
Tucannon 1	Deflector	38.6	44	90	0.149	14.4	13.5	9.2	5.6	**0.0**	**−8.7**
Tucannon 2	Deflector	37.1	24	70	0.114	**−4.7**	**−4.9**	**−4.7**	**−4.4**	**−4.2**	**−5.5**
Tucannon 3	Deflector	54.3	19	90	0.124	**−42.9**	**−64.4**	**−92.9**	**−123.6**	**−148.3**	**−166.2**
Twisp 1	Deflector	13.2	73	50	0.196	8.5	11.2	13.8	16.0	17.7	18.9
Twisp 2	Deflector	10.7	48	40	0.129	1.3	0.3	**−0.9**	**−2.3**	**−4.0**	**−5.9**
Twisp 3	Deflector	6.1	44	50	0.195	**−18.2**	**−24.1**	**−28.9**	**−32.5**	**−35.2**	**−37.5**
Twisp 4	Bar apex	29.9	31	80	0.098	**−14.6**	**−21.1**	**−26.5**	**−30.2**	**−32.7**	**−34.5**
Twisp 5	Deflector	9.5	11	60	0.226	**−3.5**	**−5.6**	**−7.8**	**−9.8**	**−11.3**	**−12.4**
Twisp 6	Deflector	12.7	17	60	0.250	5.9	7.9	8.8	8.5	7.6	7.2
Twisp 7	Deflector	20.2	31	60	0.374	4.5	5.1	4.9	3.8	2.2	0.5
Average RMSE across all jams					0.231	0.219	0.218	0.219	0.220	0.222	0.223
RMSE percent improvement across all jams						5.5%	5.7%	5.2%	4.8%	4.1%	3.4%

Note: RMSE degradations are bolded. The 4× low (α = 0.0125), 2× low (α = 0.025), and low friction scalars (α = 0.05) all offered over 5% average RMSE improvements.

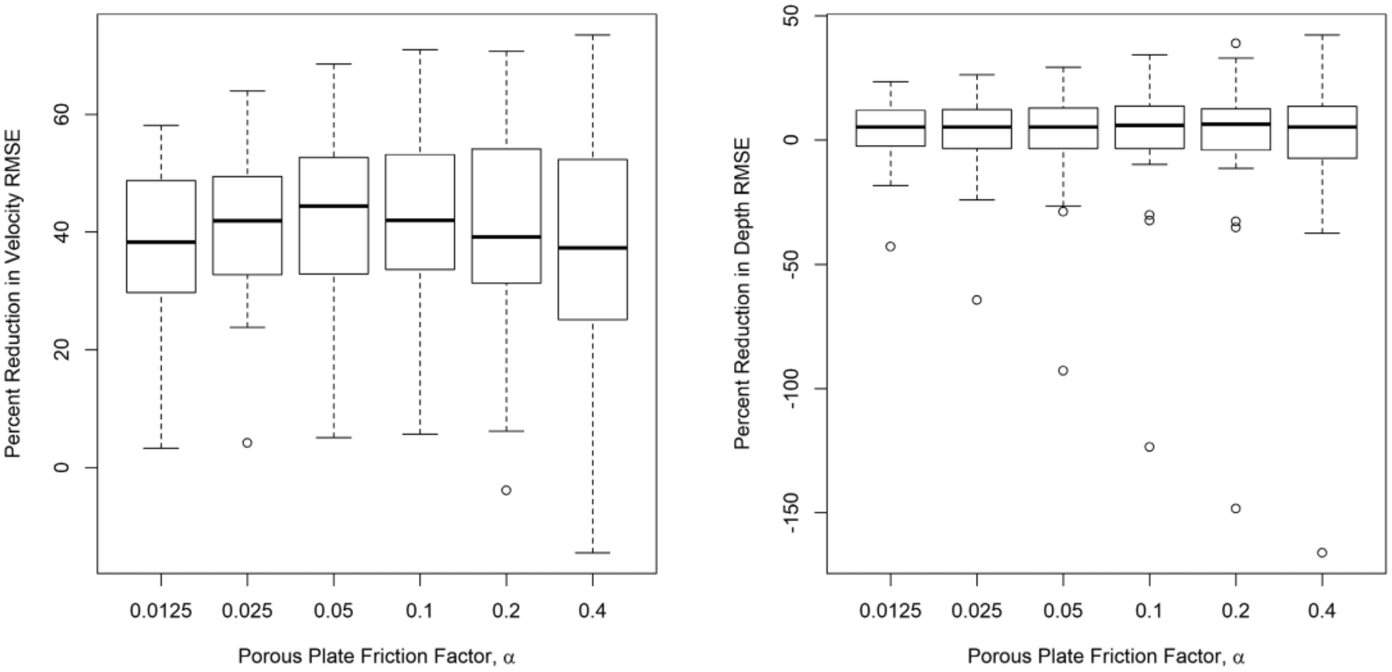


FIGURE 6. Box plots showing jam-level RMSE improvements for velocity (left) and depth (right) across all tested values of the porous plate friction factor (α).

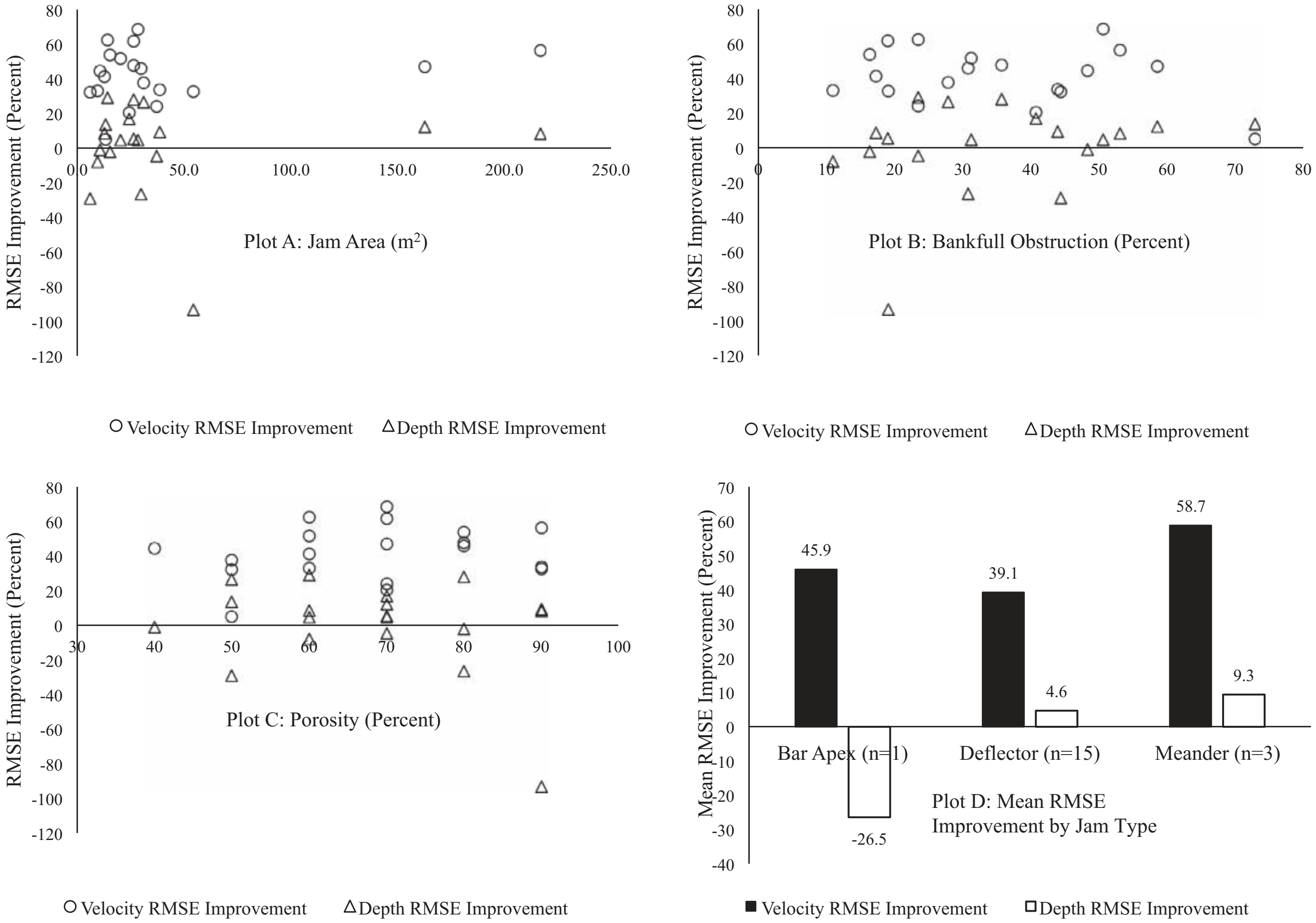


FIGURE 7. RMSE improvements ($\alpha = 0.05$) by individual LW jam based on jam characteristics: jam area (Plot A), bankfull obstruction (Plot B), porosity (Plot C), and jam type (Plot D).

TABLE 3. Spearman correlation tests for relationships between RMSE improvements and jam characteristics.

Relationship	Estimated coefficient (ρ)	p-value
Velocity RMSE improvement to jam area	0.16	0.51
Velocity RMSE improvement to bankfull obstruction	−0.05	0.82
Velocity RMSE improvement to porosity	0.22	0.35
Depth RMSE improvement to jam area	0.09	0.7
Depth RMSE improvement to bankfull obstruction	0.26	0.27
Depth RMSE improvement to porosity	−0.12	0.62

descriptions adapted from Scott et al. (2018) have not been empirically validated. Also, porosity may not be uniform across an entire LW jam structure and porosity may change over time as LW moves through a river system. Our average porosity estimate was 22% higher than an average estimate by Livers et al. (2015) (67% average porosity compared to 45% average porosity). This seemed reasonable after comparing photographs of jams from their study sites to ours. There is a general need for a tested field protocol and training materials for accurate LW jam porosity estimation. Regardless of the uncertainty in porosity estimation, we have shown that using ocular porosity estimates to calibrate jams as porous plates in hydraulic models increases the accuracy of model outputs around porous LW jams. We did not investigate the hydraulic effect of channel-spanning and very low porosity jams. We also only collected validation points under specific flow conditions, and differing flows could change each jam's impact as a flow diverter and roughness element (Wallerstein et al. 1996). Additionally, we only validated jams that occupied the entire water column, protruding above the water surface. We did not collect the same number of validation points at every jam, and at some jams validation points were limited to areas we could safely access. We recommend further investigations

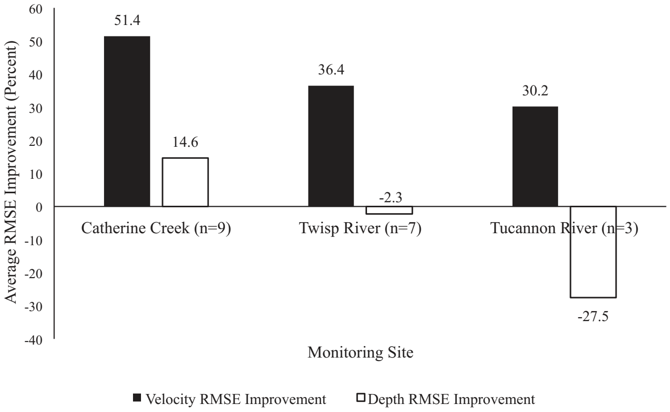


FIGURE 8. Average RMSE percent improvements by monitoring site. The greatest average improvements for both velocity and depth were observed at the Catherine Creek survey site.

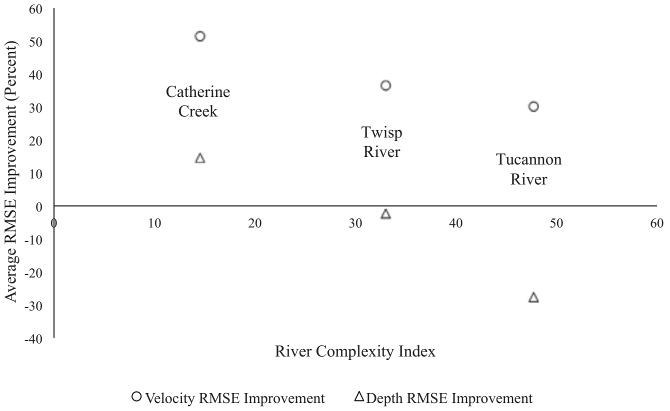


FIGURE 9. Average RMSE percent improvements by site-level river complexity index value.

exploring the use of porous plates to model a wider range of jam types and flows.

There are also limitations to our modeling approach. First of all, the linear form of our equation for converting estimated porosity into a friction factor is assumed, and may not be the most accurate representation of the relationship between porosity and flow resistance. Our friction factor input equation is consistent with Manners et al. (2007), who found that drag force decreased as porosity increased in porosity-manipulated LW jams. However, Shields and Alonso (2012) examined drag and lift coefficients for LW pieces with complex, branching geometry, finding that the greatest forces occur for simple configurations with only a few large branches, and that drag coefficients are lower as branch size decreases and branch density increases. Clearly the hydraulic forces acting upon riverine LW are complex and inherently difficult to predict. There is a general need for more data on the influence of varying LW jam porosities on hydraulics in and around a jam (Bureau of Reclamation and U.S. Army Engineer Research and Development Center 2016). Solid structures that force water to flow over or around them (e.g., jam ballast features or silt-filled jams) should be modeled as nonporous topography and may not be accurately modeled using porous plates. Additionally, any feature, porous or nonporous, that only occupies a portion of the water column (e.g., LW jams that are suspended in or over the water column, or LW jams where significant amounts of water flow over or under the jam), are not features we expect to be able to model accurately with this approach.

Despite limitations to this study and our modeling method, we were able to produce notable hydraulic model output improvements across diverse LW jams and study sites. Additionally, our study has highlighted three key research gaps:

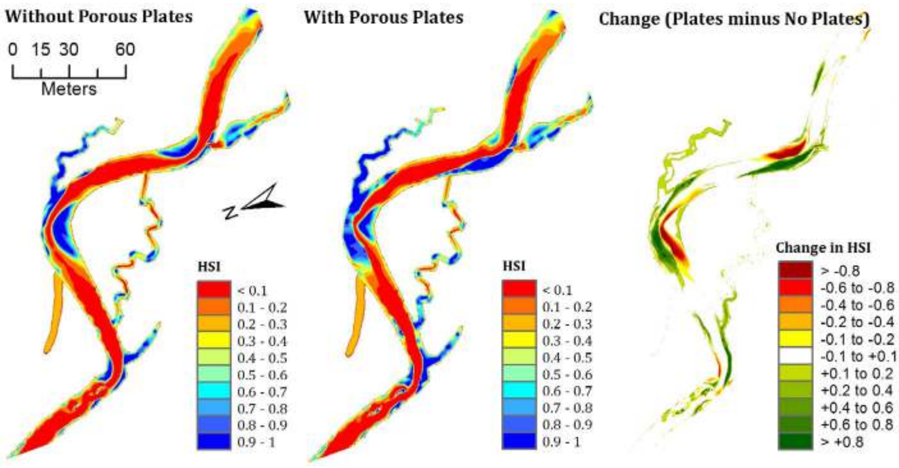


FIGURE 10. Map of depth- and velocity-based habitat suitability index (HSI) outputs for juvenile steelhead (Raleigh et al. 1984) at the Catherine Creek survey site with and without addition of porous plates to represent LW jams.

1. The need for development and validation of field protocols for accurately estimating jam porosity,
2. The need for development and validation of porous structure modeling approaches using other hydraulic modeling programs, and
3. The need for more information on how different wood jams types and porosities impact the surrounding hydraulic field.

CONCLUSION

Although there are limitations to this porous plate method, we have shown that the LW jams can be easily integrated into hydraulic modeling efforts using existing software capabilities, which dramatically improved local model outputs in our study (we reduced average velocity RMSE values by 42.8% and reduced average depth RMSE values by 5.2%). We have also shown that representation of LW jams impacts ecohydraulic models and reach assessments (the addition of porous plates at the Catherine Creek survey site resulted in an 11.5% WUA increase for juvenile Chinook and a 15.1% WUA increase for juvenile steelhead). Our study suggests that this method is scalable from the small to mid-size porous structures, though further testing is warranted before it is applied to channel-spanning structures or extremely large structures. In addition to restoration assessment, this method can be used in riverine project planning. For example, when paired with an HSI model this method could be used to evaluate the differences in habitat potential between proposed revetment designs (e.g., comparing a standard rock revetment with a revetment design that includes substantial amounts of placed LW). Additionally, this method could be used to identify local flood risks where wood has accumulated (e.g., investigating the potential backwater effect and increased water depth above an existing jam in the event of high discharge). We hope that similar porous structure modeling approaches are developed and used in other hydraulic modeling programs.

Informed river management decisions depend on accurate assessments of hydraulic and habitat conditions. Whenever possible, river investigations should consider the hydraulic contributions of LW jams.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Field jam survey protocol (Ventres-Pake 2017) and raw jam survey data (NSD 2017). Additionally, site-level bathymetric data are available through CHaMP/AEM (https://www.champmonitoring.org/ and https://www.aemonitoring.org/). All hydraulic modeling procedures, including R code and modifications for porous plate modeling, are available at South Fork Research (SFR). (https://github.com/SouthForkResearch/Hydraulic-Modeling).

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