Quantifying Restoration Success of Wood Introductions to Increase Coho Salmon Winter Habitat

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Abstract. Large wood (LW) addition is often part of fish habitat restoration projects. However, there is limited information
10 about the spatial-temporal variability in hydraulic changes after LW additions. We investigated reach scale hydraulic changes
triggered after the addition of LW that are relevant to juvenile Coho Salmon survival. We used Nays2DH, an unsteady two-
dimensional flow model to quantify patterns and magnitudes of changes of stream velocity (v) and shear stress (τ) in three
alluvial gravel reaches. The study sites are located in low gradient reaches draining 5 to 16 km^2 in the Oregon Coast Range.
Survivable habitat was characterized in terms of critical swim speed for juvenile Coho and bed stability considering the critical
15 τ required to mobilize the median bed particle size. Model predictions indicated that survivable habitat during bankfull
conditions, measured as the area with v below the critical swim speed for juvenile Coho, increased by 95–113% after the LW
restoration. Bed stability also increased between 86–128% considering the τ required to mobilize the median bed particle size.
Model predictions indicated more habitat created in the larger site, however considering that wood would move more
frequently in this site there appears to be a trade-off between the timing and the resilience of restoration benefits. Overall, this
20 study quantifies how the addition of LW potentially changes stream hydraulics to provide a net benefit to juvenile salmonid
habitat. Our findings are applicable to stream restoration efforts throughout the Pacific Northwest.

1 Introduction

Large wood (LW) is a fundamental component of many temperate streams given its influence on flow resistance, stream
morphology, sediment transport, nutrient cycling, and stream habitat (e.g., Triska and Cromack, 1980; Harmon et al., 1986;
25 Montgomery et al., 1995). LW structures increase heterogeneity in the flow field by promoting local scour and sediment
retention, by reducing average flow velocity, and by promoting increased interaction of the flow with the floodplain (Beschta,
1979; Harmon et al., 1986; Lisle, 1986; Bisson et al., 1987; Wipfli et al., 2007; Seo et al., 2008). LW jams are often associated
with forced pool-riffle morphologies in reaches that would otherwise exhibit plane-bed characteristics (Montgomery and
Buffington, 1997). Thus, channels with abundant LW have relatively higher complexity (e.g., high frequency of pools, channel
30 bars, and riffles), offering a wide range of habitat for aquatic species including invertebrates and fish (Fausch and Northcote,
1992; Roni and Quinn, 2001; Dolloff and Warren, 2003; Benke and Wallace, 2010; Pess et al., 2012). Historically, abundant

LW in Pacific Northwest streams provided habitat for a variety of fish species (Bisson et al., 1988; Connolly and Hall, 1999) including anadromous fish such as Coho Salmon (*Oncorhynchus kisutch*) and steelhead (*Oncorhynchus mykiss*) (Nickelson et al., 1992a; Quinn and Peterson, 1996; Beechie and Sibley, 1997; Johnson et al., 2005; Gallagher et al., 2014; Jones et al., 2014). Prior to the recognition of the role of LW pieces in habitat, forest management operations allowed harvesting to the edge of streams and the removal of in-channel LW. This removal resulted in the reduction stream complexity (Bisson et al., 1987; Sedell et al., 1988; Stednick, 2008), which has reduced habitat contributing to fish population declines (Dolloff, 1986; House and Boehne, 1986; Fausch and Northcote, 1992; Brown et al., 1994).

Within the freshwater habitat, overwinter survival for juvenile Coho Salmon has been identified as a critical aspect for population viability and growth (Cunjak, 1988; McMahon and Hartman, 1989; Quinn and Peterson, 1996; Huusko et al., 2007) both in the Oregon Coast Range (Nickelson et al., 1992a; Nickelson et al., 1992b; Suring et al., 2012) and the Northern California Coast (Gallagher et al., 2012). Thus, increases in low velocity winter refuge may be critical for species recovery (McMahon and Hartman, 1989; Huusko et al., 2007; NMFS, 2016).

The rationale behind LW restoration projects is that the introduced pieces would create larger and deeper pools, stabilize stream substrate, and facilitate the interaction of the flow with the floodplain. This ultimately provides low velocity refuge where juvenile salmonids can shelter both in the stream channel and in adjacent, newly connected floodplains (Bustard and Narver, 1975b; McMahon and Hartman, 1989; Bradford et al., 1995; Cunjak, 1996; Sommer et al., 2001; Jeffres et al., 2008). However, there is still controversy about the effectiveness of adding LW as a restoration strategy (Roni et al., 2008; Whiteway et al., 2010; Roni et al., 2014). Studies have reported improvements in fish abundance after LW introductions in relatively short reaches (75–500 m) (e.g., House and Boehne, 1986; Cederholm et al., 1997; Roni and Quinn, 2001) while others working over larger scales 500–1000 m have observed positive changes to stream morphology relevant to fish habitat (Anlauf et al., 2011; Jones et al., 2014). The survey approaches used in these studies provide a static perspective on stream habitat and often occur under low flow conditions. We currently lack understanding of how LW structures affect flow hydraulics and fish habitat at the reach scale under a range of flows, which is relevant to those looking to address both geomorphic change and natural habitat limitations.

Computational hydraulic modelling offers a relatively time and cost-effective strategy to analyze the flow field of a stream reach without the need for high-resolution field measurements at every discharge level of interest. Two-dimensional (2D) models have been used to quantify fish habitat based on flow velocity and depth indicators in streams in a variety of conditions (e.g., Nagaya et al., 2008; Branco et al., 2013; Cienciala and Hassan, 2013; Hatten et al., 2013; Laliberte et al., 2014; Fukuda et al., 2015; Carnie et al., 2016) but studies directly addressing the effects of LW pieces or other flow obstacles in the flow field have been limited to straight urban sections (Lee et al., 2010) or non-calibrated models (Hafs et al., 2014; Wall et al., 2016). The 2D estimate of velocity and channel bed stability, at scales of ecological significance —individual boulders and LW pieces (Crowder and Diplas, 2000) —can be used to estimate habitat improvements after the addition of LW. Flow velocity can limit the ability of fish to maintain position and result in excessive energetic costs (Huusko et al., 2007), while unstable sediment limits the ability of juveniles to find shelter within substrate rocks during high flows. Our objective

was to quantify the change in survivable habitat area for juvenile Coho Salmon after the addition of LW by examining changes in water velocity and substrate stability during a bankfull event in three gravel-bed reaches. In doing so we developed field calibrated before and after models to describe flow hydraulics in three individual sites. To our knowledge this was the first time a calibrated modelled has been used to estimate the effects of LW in natural conditions.

5 ## 2 Methods

2.1. Study Area

This study was conducted in three alluvial stream reaches in Mill Creek, a tributary of the Siletz River in the Oregon Coast Range (Fig. 1). The watershed is dominated by intensively managed Douglas fir (*Pseudotsuga menziesii*) forest, and riparian areas are mostly vegetated with the deciduous species vine maple (*Acer circinatum*), bigleaf maple (*Acer*
10 *macrophyllum*), and red alder (*Alnus rubra*). Watershed elevations range from 60 m to 730 m (Fig. 1) and the basin is primarily underlain by the Tyee formation composed of sandstone and siltstone. The climate is marine temperate, influenced by moisture from the Pacific Ocean, and annual precipitation of 230 cm in the nearby town of Siletz is mainly received as rain during fall and winter (November-March). The selected low gradient fish bearing reaches had minimal (LW) pieces present and were located in distinct geomorphic settings within the basin. Site 1 is located in the main stem of Mill Creek, Sites 2 is located in
15 Cerine Creek, and Site 3 is located in the South Fork (Table1). All sites display low to moderately developed pool riffle sequences with bankfull discharge (Q_{bf}) between 2.4 and 8.7 m³/s (Table 1).
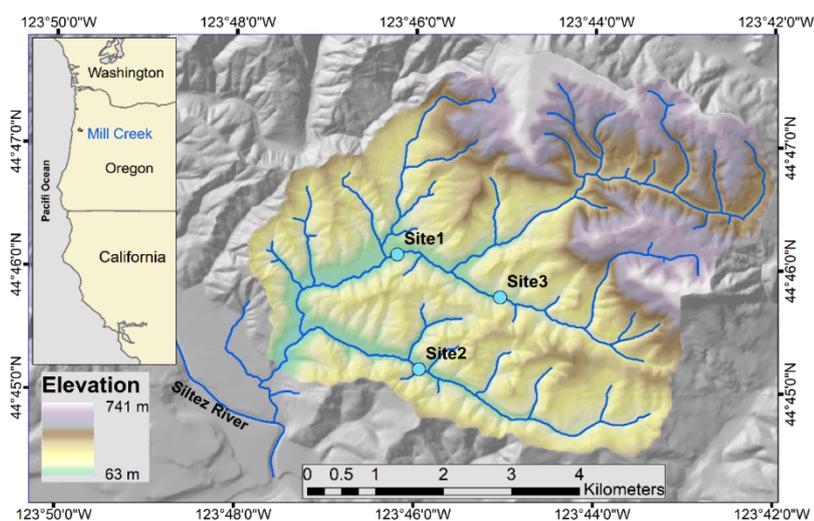

Figure 1. Location of the Mill Creek watershed, OR and the Study Sites 1, 2, and 3.

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Table 1. Characteristics of the three Study Sites. Values in parenthesis correpsond to the standard errors

Characteristic	Units	Site 1	Site 2	Site 3
Drainage area	km²	16	5	5
Length	m	119	123	115
Bankfull discharge (Q_{bf})	m³/s	8.7	2.4	2.5
Bankfull width	m	10.6 (1.9)	5.5 (0.8)	7.4 (1.6)
Bankfull depth	m	0.7 (0.2)	0.6 (0.1)	0.6 (0.1)
Bankfull area	m²	6.9 (1.8)	3.3 (0.7)	4.1 (0.9)
Slope	m/m	0.0032	0.004	0.008
D_{50}	m	0.039	0.0153	0.0297
τ_c (Mueller et al., 2005).	N/m²	16.1	6.7	16.8

2.2. Field Methods

During July of 2015, a detailed topographic survey was conducted in each of the three study reaches including 20-28 cross-sections (XS) per site spaced ~ ½ bankfull width apart and 1,700–2,000 additional survey points to characterize abrupt topographic changes. The raw topography was smoothed and interpolated to a dense point cloud using a natural neighbour scheme under ArcGIS and used in the model framework (see section 3.2). We estimated the grain size distribution (GSD) in each reach based on particle counts (Wolman, 1954) conducted in 11-25 visually identified patches of relative uniform sediment size per site (Buffington and Montgomery, 1999; Rosenberger and Dunham, 2005; Smith and Prestegaard, 2005; Cienciala and Hassan, 2013). We instrumented the study reaches with pressure transducers at a relatively stable and uniform XS (Fig. 2) and developed depth-discharge rating curves with 9-10 discharge measurements per site covering a wide range in discharge levels: 5-100% of Q_{bf} in Site 1, 5–63% of Q_{bf} in Site 2, and 5–89% of Q_{bf} in Site 3.
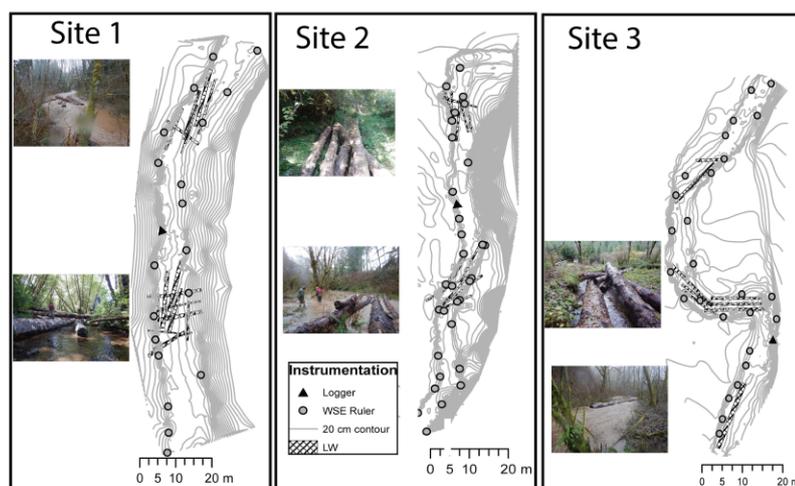

Figure 2. Topography (derived 0.2 m contours) and location of introduced large wood (LW), water surface elevation (WSE) monitoring rulers (circles), and water level loggers (triangle). Flow direction is from top to bottom in all three sites.

In August of 2015, 39 pieces of LW were added to the three sites by the Oregon Department of Fish and Wildlife. The wood was arranged into two jams per site with 3-8 wood pieces each (Fig. 2). The wood pieces added were all over 6 m

long with diameters between 0.5 m and 1.6 m. The logs were oriented lengthwise in the stream to mimic wood pieces that have been rafted into a location and provide the most contact with the bed and a stable but natural configuration to drive geomorphic change. The jams were located in bends in the stream reaches where possible, and additional logs were placed on top of jams and braced by existing trees to increase stability, but no other means of permanently fixing the jam locations was used. The
5   entire process of building the six jams across sites took less than two days.

2.3. Flow modelling

In order to describe flow field changes triggered by the addition of LW, we used the 2D unsteady Nays2DH model (Takebayashi et al., 2003; Jang and Shimizu, 2005; Shimizu and Takebayashi, 2014; Nelson et al., 2016). This model was selected for its ability to simulate unsteady conditions experienced during rapidly varying discharge and rapidly varying shear
10   stress around obstacles. We first simulated steady intermediate (20–50% of Q_{bf}) and large (Q_{bf}) flow levels for calibration purposes, and 35–45-hour long Q_{bf} flow events (unsteady) before and after the LW additions. These models were used to characterize the distributions of depth, velocity, and shear stress pre- and post-LW addition (Table 2). The model uses a free surface, finite differenced, and depth integrated version of the Navier-Stokes equations (NSE) assuming a logarithmic velocity profile in the boundary layer near the bed and a parabolic velocity profile away from it. Nays2DH uses the Cubic-Interpolated
15   Pseudo-Particle (CIP) method for finite differencing which gives high accuracy flow predictions, particularly in instances of flow separating shear layers. The model calculates present and future 2D-velocity for a given time step using a cubic profile to determine its spatial derivative under the assumption that both time steps follow the governing NSE flow equation (Yabe et al., 1990). This method requires the use of a short modelling time step to ensure model stability, thereby limiting the length of model runs given computational cost (Shimizu and Takebayashi, 2014; Nelson et al., 2016).

20   **Table 2.** Nays2DH model parameters and calibration results for pre and post large wood (LW) models for different discharge (Q) levels. Fractional bankfull discharge (Q/Q_bf); average model depth (Hmean); root mean squared error (RMSE); and R^2 for water surface elevation (WSE) and time average velocity (U) measurements are indicated for calibration runs when available.

Site	LW	Q_i (m²/s)	Q/Q_{bf}	# Nodes	H_{mean} (m)	RMSE-WSE (m)	RMSE-U (m/s)	R^2 WSE	R^2 U
1[a]	pre	4.53	0.52	60621	0.55	0.025	0.34	0.97	0.41
1[a]	pre	8.7	1.00	60621	0.71	0.033	NA	0.94	NA
1[a]	post	1.91	0.22	60621	0.57	0.078	0.16	0.94	0.39
1[b]	post	12	1.38	60621	0.98	0.211	NA	0.66	NA
2[a]	pre	1	0.41	58176	0.421	0.025	0.115	0.97	0.87
2[a]	pre	2.43	1.00	58176	0.56	0.026	0.115	0.97	0.87
2[a]	post	1.49	0.61	58176	0.53	0.039	0.249	0.98	0.75
2[b]	post	3.8	1.56	58176	0.58	0.083	NA	0.90	NA
3[a]	pre	1.08	0.49	53169	0.34	0.045	0.258	0.98	0.70
3[a]	pre	2.2	1.00	53169	0.46	0.023	0.364	1.00	0.70
3[a]	post	1.09	0.50	53169	0.55	0.037	0.29	0.99	0.69
3[b]	post	3.5	1.59	53169	0.58	0.134	NA	0.96	NA

[a] assuming a constant downstream water surface elevation as the initial boundary condition
25   [b] uniform flow assumption as the initial upstream and downstream boundary condition

Model input data were channel topography, discharge, roughness, downstream flow stage, and a characterization of the initial upstream WSE condition. Given the large size of the LW pieces with diameters 0.8–2.3 times the Q_{bf} depth in all three sites, they were represented in the model as fully penetrating the water depth protruding into the channel and located based on detailed topographic surveys. Based on time-lapse photography and flow level observations, the LW pieces were

5   never overtopped by the flow. In cases where LW pieces were angled relative to the slope of the streambed or where lateral topography in the bed left large gaps under LW pieces, the shape of the flow restricting obstacles were adjusted to allow for a significant amount of flow to pass around the structures.

The model parameters were adjusted based on 1,000 seconds constant discharge calibration simulations with 0.01-second time steps averaged over 10 iterations. We assumed a constant downstream WSE measured in the field for all

10   calibration runs except for the high flows modelled after LW addition when wading was hazardous. For these runs, and for the hydrograph simulations, we employed the uniform flow assumption as the initial upstream and downstream boundary condition (Table 2). The model equations for downstream (u) and cross-stream (v) velocity components are solved over an orthogonal, curvilinear grid (Shimizu and Takebayashi, 2014; Nelson et al., 2016) and used to estimate the shear stress (τ) via a unitless coefficient of bed shear force (C_f):

15    $$\tau = \rho C_f (u^2 + v^2) \tag{1}$$

where ρ is water density and C_f is estimated based on a spatially variable unitless Manning roughness coefficient (n) calculated for the identified sediment patches based the grain size (D), gravitational acceleration (g), flow depth (h) and an unitless prameter α parameter that can vary from 1 to 3:

$$n = \frac{(\alpha D)^{1/6}}{7.66\sqrt{g}} \tag{2}$$

20    $$C_f = \frac{n^2 g}{h^{1/3}} \tag{3}$$

Roughness values for vegetated areas outside the channel were set to be 10% higher than the maximum patch n value in each model. The best fits for all three sites were found with $\alpha = 3$ and $D=D_{84}$ (size of a particle equivalent to the 84th percentile in a cumulative frequency distribution). We chose to model turbulence using the zero-equation option in the model, which assumes smooth changes in lateral topography, and thus τ and h dominate the momentum transport. A spatially varying eddy

25   viscosity is calculated in the model as a ratio of the depth and velocity.

We calibrated the models by comparing observed and predicted WSE through each reach, with and without LW, and iteratively adjusting C_f by changing n. The root mean squared error for the WSE was below 0.05 m for all pre-wood scenarios and no more than 0.21 m for all post wood models (Table 2). Abrupt changes to streambed morphology after the addition of LW contributed to model error, as these changes could altered the observed WSE but were not reflected in our models. For

30   example, on the downstream end of Site 1 we observed significant sediment deposition on the right side of the channel and scour on the left side. Aside from this, the model was able to accurately capture the large changes in WSE across log-jams and the general water surface slope. Velocity observations were also use for calibration for 2–3 flow conditions per site when

wading was possible. The RMSE of velocity varied between 0.11–0.36 m/s (Table 2). These values are similar to other reported values of model RMSE for WSE and velocity for efforts that did not include wood; indicating overall strong performance of the model (Cienciala and Hassan, 2013; Mueller and Pitlick, 2014; Segura and Pitlick, 2015; Katz et al., 2018).

2.4 Data analysis

5   We evaluated the changes in v and τ triggered by the addition of LW in the three study reaches during a Q_{bf} flow event with emphasis on the peak discharge. Then we quantified the differences in the spatial extent of suitable habitat for juvenile Coho Salmon. For both velocity and τ distributions, only areas where depth > 0.1 m and velocity or $\tau > 0.01$ units were included to limit the study to the active channel and depths where model assumptions were not likely to be violated and to areas of the channel in which fish could be found. We estimated the area with acceptable fish habitat within the modelled domains using a

10   critical swimming velocity (v_{crit}) of 0.5 m/s and a burst swim velocity (v_{burst}) of 1 m/s for winter-time juvenile Coho Salmon (Glova and McInerney, 1977; Taylor and McPhail, 1985). The v_{crit} corresponds to the maximum velocity at which a fish can maintain position in the flow field for extended periods at a specific temperature and v_{burst} represents a maximum instantaneous swim velocity.

        Since juvenile salmonids are likely to shelter in substrate during harsh environmental conditions (Hartman, 1965;

15   Rimmer et al., 1983; Bradford et al., 1995; Cunjak, 1996; Bradford and Higgins, 2001), we used the predicted τ values to estimate the proportion of the bed area in which the entrainment of the D_{50} is likely. Indeed, the D_{50} values in the study sites range from 16–39 mm which is similar to the particle size in which sheltering juvenile Atlantic salmon have been observed (Cunjak, 1988). Our assumption is that transport of the D_{50} is a reasonable threshold to represent conditions in which dislodging fish is possible because the substrate would fail to provide shelter. The critical shear stress (τ_c) associated with the movement

20   of the D_{50} was estimated based on slope (s) (Mueller et al., 2005):

$$\tau_c^* = 2.18s + 0.021 \qquad (4)$$

$$\tau_c^* = \frac{\tau_c}{(\rho_s - \rho)gD_{50}} \qquad (5)$$

where τ_c^* is the dimensionless critical Shield's stress and ρ_s is sediment density (i.e., 2,500 kg/m³ for sandstone). We assumed that channel bed locations with $\tau > 2\tau_c$ are likely to experience full transport mobility (Wilcock and McArdell, 1993), and

25   therefore offer no fish sheltering given that most of the available particles sizes would likely be mobilized. In sections of the bed experiencing partial transport ($\tau_c < \tau < 2 \tau_c$) we assumed that sheltering would be difficult but not impossible as larger particles are likely to remain stable.

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3 Results

3.1 Comparison of velocity before and after the addition of LW

According to model predictions the mean bankfull flow velocity (*v*) before LW additions ranged between 0.7 m/s and 1.2 m/s while after the addition of LW pieces *v* ranged between 0.53 m/s and 0.92 m/s (Table 3) corresponding to 23.2–36.3%

5　decreases. The distributions of *v* values at wetted points throughout the model domain were narrower before LW was added than the distributions after the LW (Fig. 3). Before the restoration, all *v* distributions exhibited a high density of observations around the mean values (Fig. 4) and relatively small standard deviations (0.3 m/s to 0.5 m/s, Table 3). After the LW additions, the flow fields became more heterogeneous (standard deviations between 0.4 m/s and 0.7 m/s, Table 3) with lower clustering of *v* values around the mean and a greater proportion of areas in the channel bed that experienced extreme (low and high) *v*

10　conditions (Fig. 3 and 4). The increased heterogeneity of flow conditions was associated with a greater proportion of flow interacting with the floodplains upstream of the LW jams and the flow passing through the decreased cross-sectional area of the LW jams themselves.

Table 3. Mean and standard deviation (SD) of velocity (*v*) and shear stress (*τ*) at bankfull flow (Q_{bf}) pre- and post-LW at the three study sites; Q_{bf} modelling results for habitat metrics *v* and *τ* expressed as a percentage of the channel bed pre- and post-

15　LW; and percentage change in available fish habitat.

Metric	Site 1		Site 2		Site 3	
	Pre-LW	Post-LW	Pre-LW	Post-LW	Pre-LW	Post-LW
Mean *v* (SD)	1.23 (0.5)	0.92 (0.7)	0.69 (0.3)	0.53 (0.4)	1.02 (0.5)	0.65 (0.5)
Mean *τ* (SD)	23.41 (14.7)	18.99 (29.7)	12.24 (8)	9.14 (11.8)	22.27 (18.2)	11.35 (16.8)
% of Bed						
$v \le v_{crit}$[a]	15.3	32.5	26.7	52.2	23.8	47.3
$v_{crit} \le v \le v_{burst}$[a]	13.9	32.7	60.2	34.5	17.0	28.3
$v > v_{burst}$[a]	70.8	34.8	13.1	13.3	59.2	24.4
$\tau < \tau_c$[b]	30.2	69.0	29.1	59.9	41.0	76.4
$\tau_c < \tau < 2\tau_c$[b]	43.9	12.6	23.4	17.9	35.3	14.8
$\tau < 2\tau_c$[b]	25.8	18.4	47.5	22.2	23.7	8.9
% Change in Available Habitat						
$v \le v_{crit}$[a]	+112.8%		+95%		+99.3%	
$v_{crit} \le v \le v_{burst}$[a]	+134.5%		-42.6%		+66.1%	
$v > v_{burst}$[a]	-50.8%		+1.4%		-58.8%	
$\tau < \tau_c$[b]	+128.3%		+105.9%		+86.3%	
$\tau_c < \tau < 2\tau_c$[b]	-71.4%		-23.5%		-58.2%	
$\tau < 2\tau_c$[b]	-28.8%		-53.3%		-62.6%	

[a]v_{crit} is 0.5 m/s and v_{burst} = 1 m/s
[b]τ_c is the critical shear stress for the movement of the median grain size (Table 1)

Reduced *v* in the stream channels after the addition of LW predicted increased fish habitat in all sites. The proportion

20　of the wetted channel area with *v* values below the critical ($v \le v_{crit}$) increased over 95% in all sites (Table 3, Fig. 3) being highest in Site 1. The absolute increases in the total area where $v \le v_{crit}$ were even greater at 186.1%, 141.2%, and 169.5% for

sites 1-3 respectively. These values may be more relevant to restoration success in the context of density dependent habitat limitations faced by juvenile Coho Salmon. The LW pieces backed up flow, increasing the wetted width, which resulted in additional low v habitat created beyond the original channel margins (Fig. 3). Hence, the wetted areas of sites 1, 2 and 3 increased by 34%, 22%, and 35% respectively (Fig. 3). The areas with temporarily acceptable habitat ($v_{crit} \leq v \leq v_{burst}$) also

5 increased in sites 1 and 3 from 13.9% and 17.0 % to 32.7% and 28.3% of the wetted channel area (Table 3). Conversely, temporarily acceptable habitat decreased from 60.2% to 34.5% of the wetted bed in Site 2 (Table 3). This site had proportionally more areas with $v < v_{burst}$ prior to the LW introductions (light blue in Fig. 3) and therefore less potential for an increase in that category. These observations clearly indicate that the LW additions increased the area of habitat acceptable for juvenile salmon at Q_{bf}.

10 As mentioned above the v distributions changed in shape with the highest frequency values shifting away from the value of v_{burst} to below or near the value of v_{crit}, hence the skewness of the distributions shifted from negative to positive values in all sites. This shift provides assurance of the resiliency of our results. If the thresholds used to determine habitat acceptability were shifted slightly, to account for variations in other habitat parameters such as water temperature or fish size, the benefits predicted by our model results would remain consistent.
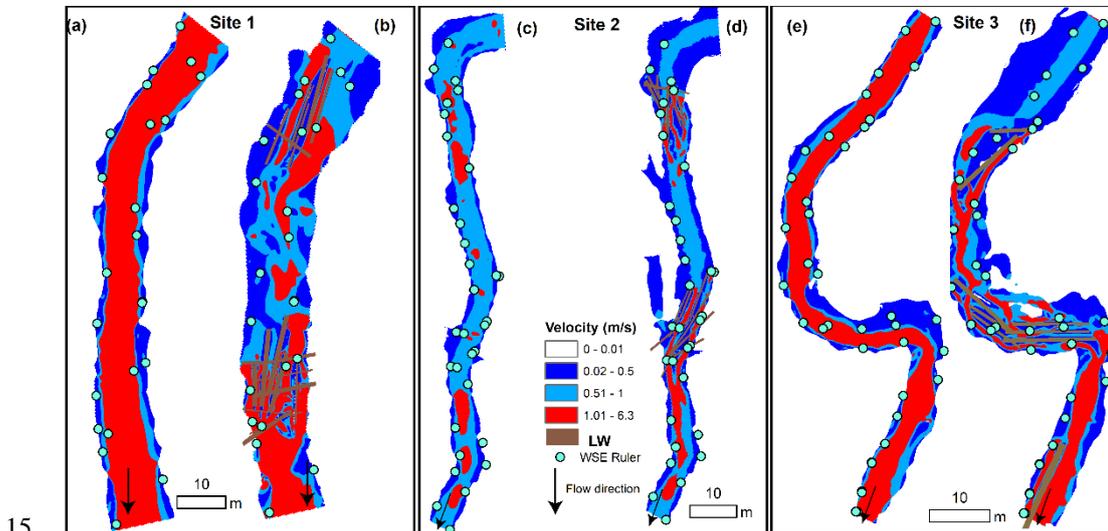

Figure 3. Mean flow velocity at bankfull discharge before (a, c, and e) and after (b, d, and f) the addition of large wood (LW) in Sites 1, 2, and 3. The colors correspond to thresholds of velocity relevant to the ability of juvenile Coho Salmon to maintain position in the stream: dark blue means $v < v_{crit}$ where $v_{crit} = 0.5$ m/s, light blue means $v_{crit} < v < v_{burst}$ where $v_{burst} = 1$ m/s, and red means $v > v_{burst}$. The location of the installed water surface rulers is included to facilitate visual comparison of the

20 increase extend of floodplain inundation in each site during bankfull conditions.

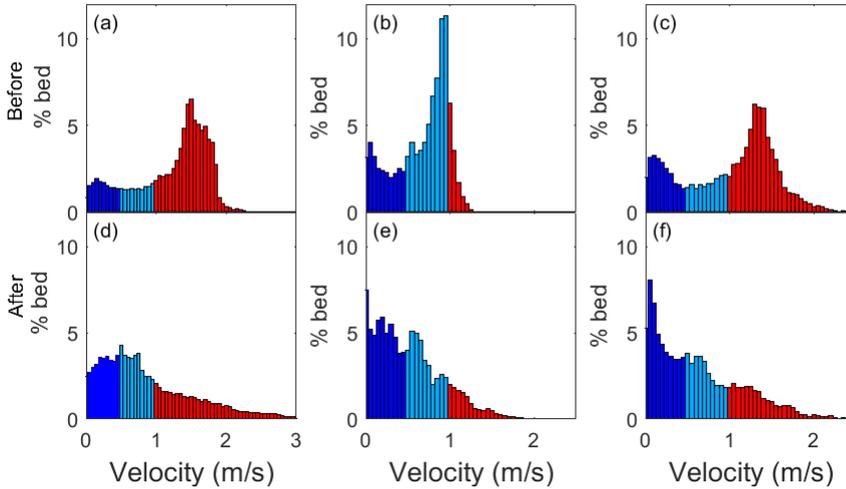Earth **Surface**
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Figure 4. Velocity distributions at bankfull flow at Sites 1 (a, d), 2 (b, e) and 3 (c, f) before (a-c) and after (d-f) the addition of large wood (LW). The colors correspond to thresholds of velocity relevant to the ability of juvenile Coho Salmon to maintain position in the stream: dark blue means $v < v_{crit}$ where $v_{crit} = 0.5$ m/s, light blue means $v_{crit} < v < v_{burst}$ where $v_{burst} = 1$ m/s, and red means $v > v_{burst}$.

3.2 Comparison of shear stress before and after the addition of LW

Model predictions indicated that the reach-average Q_{bf} values of shear stress (τ) before the LW additions were 23.41 N/m² in Site 1, 12.24 N/m² in Site 2, and 22.27 N/m² in Site 3 (Table 3). These values decreased 18–49% after the LW pieces were added, which resulted in substantial increase of fish habitat in terms of substrate stability. Considering the critical Shields value for the median grain size (Table 1), the proportions of the wetted bed with stable conditions ($\tau < \tau_c$) increased from 29–41% before LW to 59.9–76.4% after wood was added—an overall increase in fish habitat of 86–128% (Table 3). Further, the total increases in absolute area where $\tau < \tau_c$ were 205.8% for Site 1, 151.4% for Site 2, and 151.6% for Site 3 (Fig. 5). The spatial changes in the distributions of τ were associated with consistent decreases in flow v near the channel margins and additional stream connectivity with available floodplains (Fig. 6). Considering that there were a significant number of observations, that lie below the chosen transport threshold (τ_c), our assessment of the potential increase in fish habitat is somewhat independent of it (Fig. 5). For instance, if we decrease or increase the τ_c by 20% the overall increase of fish habitat would still be significant and between 72% and 149%.
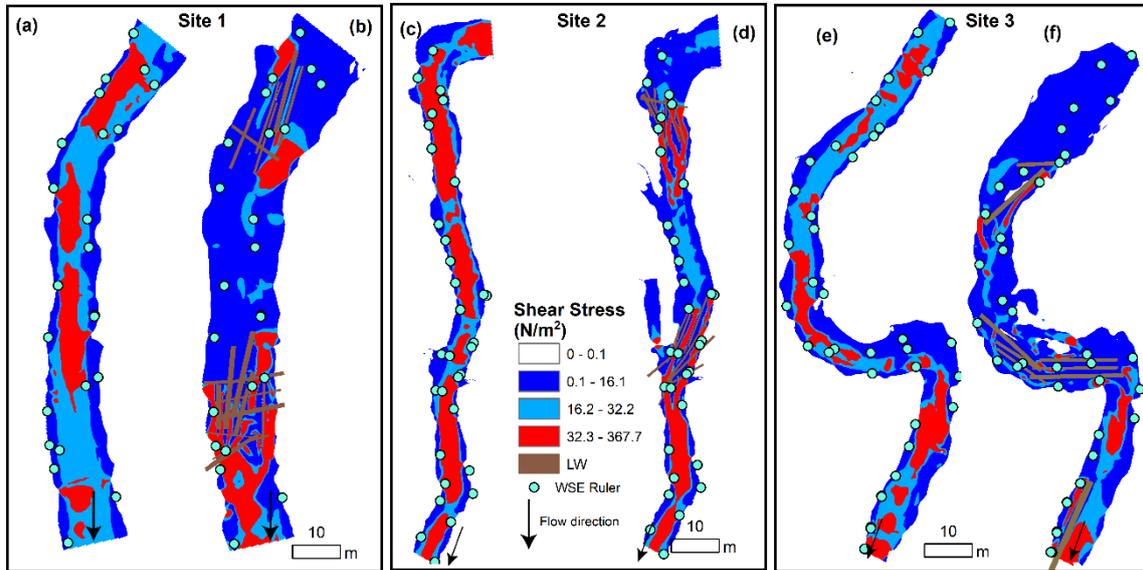
Figure 5. Spatial distributions of shear stress (τ) at bankfull discharge before (a, c, and e) and after (b, d, and f) the addition of large wood (LW). Dark blue corresponds to $\tau < \tau_c$, light blue corresponds to $\tau_c < \tau < 2\tau_c$, and red corresponds to $\tau > 2\tau_c$. The location of the installed water surface rulers is included to facilitate visual comparison of the increase extend of floodplain inundation in each site during bankfull conditions.

The shape of the distributions of τ changed, from having a distinct peak near the mean in addition to a high frequency of observations near zero, to a distribution characterized by a constant decay (Fig. 6). We fitted the mean normalized distributions of τ before and after the LW additions to a gamma function and found that the shape parameter of the distributions decreased for all sites. While this parameter before LW varied between 2.2 and 3.6 it varied between 0.6 and 1.0 after the LW additions. These changes illustrate increases in complexity in the flow field after the restoration project.
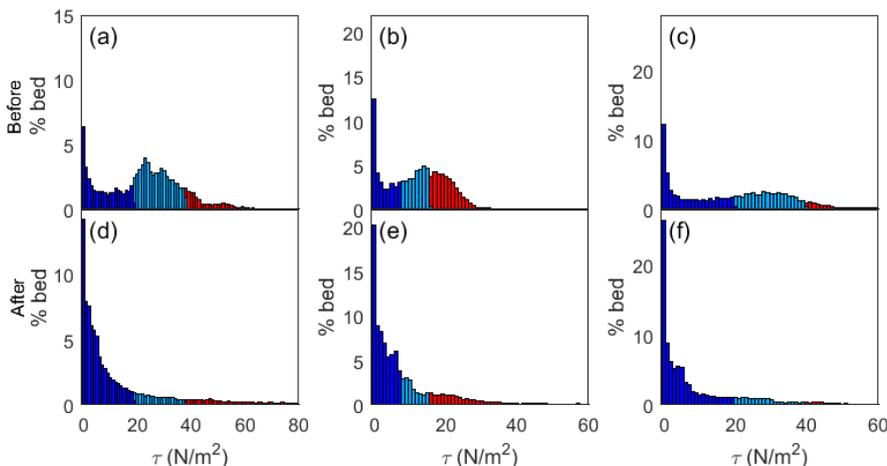

Figure 6. Shear Stress (τ) distributions at bankfull flow at sites 1 (a, d), 2 (b, e) and 3 (c, f) before (a-c) and after (d-f) the addition of large wood (LW). Dark blue corresponds to $\tau < \tau_c$, light blue corresponds to $\tau_c < \tau < 2\tau_c$, and red corresponds to $\tau > 2\tau_c$.

Discussion

The goal of this study was to model the hydraulic effects of the introduction of LW on components of fish habitat in three gravel bed streams. Two-dimensional (2D) modelling predicted significant changes in the flow field pre- and post-LW additions that resulted in approximately twice as much winter rearing habitat in all sites. To our knowledge, this study is the

5 first to simulate the impact of the addition of LW on fish habitat at the reach scale using a field calibrated, unsteady 2D hydraulic model, calibrated to pre and post LW flow events. Our findings concur with uncalibrated and steady state simulations that have documented increases the heterogeneity in the flow field at high discharges after the addition of LW, thereby increasing fish habitat (He et al., 2009; Hafs et al., 2014; Wall et al., 2016). The use of water surface elevation and v calibration data in pre- and post-LW models provided a robust framework to estimate mean depth-averaged flow v and shear τ, variables

10 likely to fully represent realistic winter sheltering opportunities for juvenile fish in terms of flow v and substrate stability.

The addition of LW in the study reaches modified river hydraulics, resulting in significantly wider wetted areas. At bankfull flow, the increased floodplain connectivity was associated with more heterogeneous flow fields characterized by wider distributions of v and τ with overall lower mean values. The shapes of pre-LW v distributions for all sites were similar to those observed in small mountain streams with large frequency at both intermediate and low v values (Cienciala and Hassan,

15 2016). The shape of the v distributions changed dramatically post-LW being characterized by a higher proportion of low v areas in all three sites. Other field modelling efforts have documented similar effects of LW on the v distribution in the flow field (Wall et al., 2016). Flume experiments as well as field simulations have also reported reductions in flow v with increasing large wood obstacles (He et al., 2009; Davidson and Eaton, 2013; Hafs et al., 2014). The distributions of τ also changed dramatically from closely resembling those observed in single thread streams pre-LW (Lisle et al., 2000; Mueller and Pitlick,

20 2014; Segura and Pitlick, 2015; Cienciala and Hassan, 2016) to resembling complex braided channels (Paola, 1996; Nicholas, 2003; Mueller and Pitlick, 2014; Tamminga et al., 2015) post-LW. The shift towards a greater frequency of low τ is likely attributed to τ partition by the channel banks and LW form drag (Kean and Smith, 2006; Yager et al., 2007; Ferguson, 2012; Scheingross et al., 2013). The changes in the v and τ distributions occurred as the flow encroached into the floodplain, and although stream margins have been associated with the creation of off-channel habitat for juvenile Coho Salmon in previous

25 studies (Swales and Levings, 1989; Bell et al., 2001), no quantification of the actual changes in the flow field in terms of v or τ had been conducted before. The post-LW distributions of τ and v indicated increased hydraulic and habitat heterogeneity (Gerhard and Reich, 2000; Brooks et al., 2006), which has been reported as a key flow field characteristic associated for habitat suitability for salmonids (McMahon and Hartman, 1989; Roni and Quinn, 2001; Venter et al., 2008; Anlauf-Dunn et al., 2014). The suggested benefits of flow heterogeneity include v refuges in close proximity to feeding locations and cover from predators

30 (Nickelson et al., 1992a; Nickelson and Lawson, 1998; Gustafsson et al., 2012). The increase availability of low v areas during bankfull discharge is relevant for winter fish habitat given the high mortality that can occur during this season (Quinn and Peterson, 1996). Although we did not measure sediment transport, the overall reduction of v and τ likely contributes to

increased pool depth and area (Montgomery et al., 1995; Beechie and Sibley, 1997; Collins et al., 2002) and decreased overall bed load transport capacity (Thompson and Fixler, 2017; Wohl and Scott, 2017).

Although we were able to model v and τ, there are components of the flow and temporal changes to the bed that we were unable to account for. While the sharp topography in our model domains around LW pieces allowed us to predict local

5 areas of elevated τ, the 2D model is not capable of capturing the strong vertical currents that are likely to develop in proximity to the LW and deform the stream bed (Mutz et al., 2007). A 3D version of the NAYS2DH model, known as NaysCUBE, could potentially address some of these issues. However, this approach would require substantially more time, computational power, and calibration to ensure model stability. As the bed deforms, we would expect to see a feedback of changing v and τ values, particularly where we predicted the highest values. Another limitation of our approach is the inability to account for LW

10 mobility. Field observations during high flows and the length of LW pieces relative to stream widths, indicate that pieces were unlikely to mobilize downstream (Merten et al., 2010; Ruiz-Villanueva et al., 2016); however, we did observe some floating and minor adjustment of some LW pieces (particularly in Site 1) during the highest flow events. Thus localized stream hydraulics could be subject to variations including potential flow underneath LW pieces, via both scour and hyporheic flow through sediment (Ruiz Villanueva et al., 2014) that we did not account for in the model.

15 Despite these uncertainties, the strong agreement between observed and predicted water surface elevation and v before and after the LW additions provided evidence that the predictions are robust. This implies that this unsteady model, which has traditionally been used in larger systems (Kafle and Shakya, 2018) can be implemented in significantly smaller systems even in the presence of large obstacles. Though it is key that sufficient detail on channel morphology the regions where LW blocks flow is available to allow for conveyance through the model domain in such small streams. The changes in the flow field we

20 documented clearly show that the addition of LW created more of the slow water habitat preferred by juvenile Coho Salmon during the winter. The observed shift in v distribution toward very low water velocities, particularly evident at Sites 2 and 3, may be especially important due to the energetic challenges faced by Coho Salmon in winter when food resources and assimilation capabilities are limited (Cunjak, 1996; Huusko et al., 2007). Juvenile Coho Salmon are generally found in microhabitats with water velocities far below v_{cr} in the winter (Bustard and Narver, 1975a; McMahon and Hartman, 1989), and

25 the availability of such habitats, especially during high flows, may be a critical factor in increasing overwinter survival. The spatial arrangement of these low v habitats relative to water depth and cover in the form of woody debris and overhanging banks is also important, as these factors affect the risk of displacement and predation for juvenile Coho Salmon (Bustard and Narver, 1975b; Tschaplinski and Hartman, 1983; McMahon and Hartman, 1989). Given the importance of multiple factors in winter habitat selection by Coho Salmon, incorporating v, depth, and cover into the habitat- modelling process would be a

30 useful future direction for predicting the effects of LW addition on habitat suitability.

Considering that after the restoration project the flow field in the study reaches is adjusting to the new condition the model predictions will progressively lose accuracy as channel scouring and aggradation occur around and behind the new LW additions. The period over which the predictions would be robust is uncertain and would depend on how fast the streams adjust

to the new conditions and how stable the LW additions are. Both the stability of individual LW pieces and its function in the flow field depend of the size of the LW piece relative to the size of the stream. Modelling predictions indicated more habitat created in the large reach (Site 1) compared to the smaller reaches (Sites 2 and 3) both in terms of v and τ (Table 3). However, the introduced LW would likely be more stable in the smaller sites than in larger sites (Gurnell et al., 2002; Hassan et al., 2005;

5 Wohl and Jaeger, 2009; Merten et al., 2010; Ruiz-Villanueva et al., 2016). Therefore, we anticipate that the model predictions will lose accuracy sooner in the larger site and that there may be a trade-off between the timing and the resilience of restoration benefits. That is the addition of LW would likely increase the amount of suitable habitat sooner in the larger site but the LW pieces in this site also have the highest potential to leave the system. In order to test this expectation the model could be run again with updated topography to explore how the predicted distributions of shear stress and velocity presented in this study

10 compare to new estimations after the bed has adjusted. This would provide not only a way to contrast model predictions but to understand which site is changing faster after the restoration and what habitat benefits are likely to persist in the longer term (Wall et al., 2016). This trade-off relative to stream size and potential to LW export also highlight the importance of considering restoration in a basin wide context.

Although we focused on juvenile Coho Salmon in our analysis, the modelling results are highly relevant to other

15 salmonid species in these streams, as well as to other life history stages. For example, the critical swimming speed of juvenile steelhead trout falls between the v_{crit} and v_{burst} values for Coho Salmon used in our analysis (Hawkins and Quinn, 1996), and so the amount of suitable habitat for juvenile steelhead following LW addition would also be expected to increase significantly. Furthermore, juvenile steelhead are more oriented to the stream bottom in winter than Coho Salmon, with age-0 steelhead often using substrate as cover (Bustard and Narver, 1975a). As a result, the increased bed stability we observed post-LW would

20 likely have an even stronger effect on habitat suitability for juvenile steelhead than for Coho Salmon. Changes in shear stress and bed stability can also have important effects on the survival of salmonid embryos incubating in the substrate (Lisle and Lewis, 1992), and our sites are located in important spawning areas for adult Coho Salmon and steelhead in the study basin. More detailed examination of spawning sites, sediment transport, and scour depths would be needed to fully investigate effects of LW on salmonid embryo survival, but the modelling approach used here could provide valuable insight into the spatial

25 distribution of shear stress in a study of this kind.

Conclusions

In this study, we used an unsteady two-dimensional hydraulic model to investigate the effects of the introduction of large wood (LW) on fish habitat in three gravel bed streams. The models predicted habitat increases in terms of suitable flow velocity and area of stable substrate of over 80% in all streams. Our study is the first to use a field-calibrated model to estimate

30 river hydraulics pre- and post-LW at the reach scale. The distributions of velocity and shear stress changed dramatically from bimodal to exponential decay, indicating increased flow complexity in the presence of LW and resembling a change from single thread to multithread channels. We observed larger changes in the largest site, however we anticipate a trade-off between

the timing and the resilience of restoration benefits given the higher likelihood for wood transport in the larger site. The methodology presented here can be used in the future as a tool to predict changes triggered by restoration efforts, evaluate long-term responses to restoration, and assess the changes in the flow field of different LW scenarios to improve our understanding of LW dynamics in streams outside of flume experiments. Finally, although the primary fish species of interest

5   in Mill Creek is Coho Salmon, our results are relevant to other salmonids and non-salmonids that also benefit from reduced v and increased channel bed stability.

Data availability. Nays2D predicted distributions of velocity and shear stress are currently being process at ScholarsArchive@OSU and will be publically available soon.   If the files are required sooner for the review please contact

10   Catalina Segura (segurac@oregonstate.edu).

References

Anlauf-Dunn, K. J., Ward, E. J., Strickland, M., and Jones, K.: Habitat connectivity, complexity, and quality: predicting adult coho salmon occupancy and abundance, Canadian Journal of Fisheries and Aquatic Sciences, 71, 1864-1876, 2014.
Anlauf, K. J., Gaeuman, W., and Jones, K. K.: Detection of Regional Trends in Salmonid Habitat in Coastal Streams, Oregon, Transactions
20   of the American Fisheries Society, 140, 52-66, 2011.
Beechie, T. J. and Sibley, T. H.: Relationships between channel characteristics, woody debris, and fish habitat in northwestern Washington streams, Transactions of the American Fisheries Society, 126, 217-229, 1997.
Bell, E., Duffy, W. G., and Roelofs, T. D.: Fidelity and Survival of Juvenile Coho Salmon in Response to a Flood, Transactions of the American Fisheries Society, 130, 450-458, 2001.
25   Benke, A. C. and Wallace, J. B.: Influence of wood on invertebrate communities in streams and rivers, In: Gregory, S.V.; Boyer, K.L; Gurnell, A.M. eds. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37: Bethesda, Maryland. p. 149-177., 37, 149-177, 2010.
Beschta, R. L.: Debris removal and its effects on sedimentation in an Oregon Coast Range stream, Northwest Science, 53, 71–77., 1979.
Bisson, P. A., Bilby, R. E., Bryant, M. D., Dolloff, C. A., Grette, G. B., House, R. A., Murphy, M. L., Koski, K. V., and Sedell, J. R.: Large
30   woody debris in forested streams in the Pacific Northwest: past, present, and future, 1987. 1987.
Bisson, P. A., Sullivan, K., and Nielsen, J. L.: Channel hydraulics, habitat use, and body form of juvenile coho salmon, steelhead, and cutthroat trout in streams, Transactions of the American Fisheries Society, 117, 262-273, 1988.
Bradford, M. J. and Higgins, P. S.: Habitat-, season-, and size-specific variation in diel activity patterns of juvenile chinook salmon (Oncorhynchus tshawytscha) and steelhead trout (Oncorhynchus mykiss), Canadian Journal of Fisheries and Aquatic Sciences,
35   58, 365-374, 2001.
Bradford, M. J., Taylor, G. C., Allan, J. A., and Higgins, P. S.: An Experimental Study of the Stranding of Juvenile Coho Salmon and Rainbow Trout during Rapid Flow Decreases under Winter Conditions, North American Journal of Fisheries Management, 15, 473-479, 1995.

Branco, P., Boavida, I., Santos, J. M., Pinheiro, A., and Ferreira, M. T.: Boulders as building blocks: improving habitat and river connectivity for stream fish, Ecohydrology, 6, 627-634, 2013.

Brooks, A. P., Howell, T., Abbe, T. B., and Arthington, A. H.: Confronting hysteresis: Wood based river rehabilitation in highly altered riverine landscapes of south-eastern Australia, Geomorphology, 79, 395-422, 2006.

5   Brown, L. R., Moyle, P. B., and Yoshiyama, R. M.: Historical Decline and Current Status of Coho Salmon in California, North American Journal of Fisheries Management, 14, 237-261, 1994.

Buffington, J. M. and Montgomery, D. R.: A procedure for classifying textural facies in gravel-bed rivers, Water Resour. Res., 35, 1903-1914, 1999.

Bustard, D. R. and Narver, D. W.: Aspects of the Winter Ecology of Juvenile Coho Salmon (Oncorhynchus kisutch) and Steelhead Trout

10   (Salmo gairdneri), Journal of the Fisheries Research Board of Canada, 32, 667-680, 1975a.

Bustard, D. R. and Narver, D. W.: Preferences of juvenile coho salmon (*Oncorhynchus-kisutch*) and cutthroat trout (*Salmo-clarki*) relative to simulated alteration of winter habitat, Journal of the Fisheries Research Board of Canada, 32, 681-687, 1975b.

Carnie, R., Tonina, D., McKean, J. A., and Isaak, D.: Habitat connectivity as a metric for aquatic microhabitat quality: application to Chinook salmon spawning habitat, Ecohydrology, 9, 982-994, 2016.

15   Cederholm, C. J., Bilby, R. E., Bisson, P. A., Bumstead, T. W., Fransen, B. R., Scarlett, W. J., and Ward, J. W.: Response of Juvenile Coho Salmon and Steelhead to Placement of Large Woody Debris in a Coastal Washington Stream, North American Journal of Fisheries Management, 17, 947-963, 1997.

Cienciala, P. and Hassan, M. A.: Linking spatial patterns of bed surface texture, bed mobility, and channel hydraulics in a mountain stream to potential spawning substrate for small resident trout, Geomorphology, 197, 96-107, 2013.

20   Cienciala, P. and Hassan, M. A.: Sampling variability in estimates of flow characteristics in coarse-bed channels: Effects of sample size, Water Resour. Res., 52, 1899-1922, 2016.

Collins, B. D., Montgomery, D. R., and Haas, A. D.: Historical changes in the distribution and functions of large wood in Puget Lowland rivers, Canadian Journal of Fisheries and Aquatic Sciences, 59, 66-76, 2002.

Connolly, P. J. and Hall, J. D.: Biomass of coastal cutthroat trout in unlogged and previously clear-cut basins in the central coast range of

25   Oregon, Transactions of the American Fisheries Society, 128, 890-899, 1999.

Crowder, D. W. and Diplas, P.: Using two-dimensional hydrodynamic models at scales of ecological importance, Journal of Hydrology, 230, 172-191, 2000.

Cunjak, R. A.: Behavior and microhabitat of young atlantic salmon (salmo-salar) during winter, Canadian Journal of Fisheries and Aquatic Sciences, 45, 2156-2160, 1988.

30   Cunjak, R. A.: Winter habitat of selected stream fishes and potential impacts from land-use activity, Canadian Journal of Fisheries and Aquatic Sciences, 53, 267-282, 1996.

Davidson, S. L. and Eaton, B. C.: Modeling channel morphodynamic response to variations in large wood: Implications for stream rehabilitation in degraded watersheds, Geomorphology, 202, 59-73, 2013.

Dolloff, C. and Warren, M. L., Jr.: Fish relationships with large wood in small streams, American Fisheries Society Symposium 37:, 37,

35   179-193, 2003.

Dolloff, C. A.: Effects of stream cleaning on juvenile coho salmon and dolly varden in Southeast Alaska, Transactions of the American Fisheries Society, 115, 743-755, 1986.

Fausch, K. D. and Northcote, T. G.: Large Woody Debris and Salmonid Habitat in a Small Coastal British Columbia Stream, Canadian Journal of Fisheries and Aquatic Sciences, 49, 682-693, 1992.

40   Ferguson, R. I.: River channel slope, flow resistance, and gravel entrainment thresholds, Water Resour. Res., 48, doi: 10.1029/2011wr010850, 2012.

Fukuda, S., Tanakura, T., Hiramatsu, K., and Harada, M.: Assessment of spatial habitat heterogeneity by coupling data-driven habitat suitability models with a 2D hydrodynamic model in small-scale streams, Ecological Informatics, 29, 147-155, 2015.

Gallagher, S. P., Ferreira, J., Lang, E., Holloway, W., and Wright, D. W.: Investigation of the relationship between physical habitat and

45   salmonid abundance in two coastal northern California streams, California Fish and Game, 100, 683-702, 2014.

Gallagher, S. P., Thompson, S., and Wright, D. W.: Identifying factors limiting coho salmon to inform stream restoration in coastal Northern California, California Fish and Game, 98, 185-201, 2012.

Gerhard, M. and Reich, M.: Restoration of Streams with Large Wood: Effects of Accumulated and Built-in Wood on Channel Morphology, Habitat Diversity and Aquatic Fauna, International Review of Hydrobiology, 85, 123-137, 2000.

50   Glova, G. J. and McInerney, J. E.: Critical Swimming Speeds of Coho Salmon (Oncorhynchus kisutch) Fry to Smolt Stages in Relation to Salinity and Temperature, Journal of the Fisheries Research Board of Canada, 34, 151-154, 1977.

Gurnell, A. M., Piegay, H., Swanson, F. J., and Gregory, S. V.: Large wood and fluvial processes, Freshwater Biology, 47, 601-619, 2002.

Gustafsson, P., Greenberg, L. A., and Bergman, E. V. A.: The influence of large wood on brown trout (Salmo trutta) behaviour and surface foraging, Freshwater Biology, 57, 1050-1059, 2012.

55   Hafs, A. W., Harrison, L. R., Utz, R. M., and Dunne, T.: Quantifying the role of woody debris in providing bioenergetically favorable habitat for juvenile salmon, Ecological Modelling, 285, 30-38, 2014.

Harmon, M. E., Franklin, J. F., Swanson, F. J., Sollins, P., Gregory, S. V., Lattin, J. D., Anderson, N. H., Cline, S. P., Aumen, N. G., Sedell, J. R., Lienkaemper, G. W., Cromack, K., and Cummins, K. W.: Ecology of Coarse Woody Debris in Temperate Ecosystems, Advances in Ecological Research, 15, 133-302, 1986.

Hartman, G. F.: The Role of Behavior in the Ecology and Interaction of Underyearling Coho Salmon (Oncorhynchus kisutch) and Steelhead Trout (Salmo gairdneri), Journal of the Fisheries Research Board of Canada, 22, 1035-1081, 1965.

Hassan, M. A., Church, M., Lisle, T. E., Brardinoni, F., Benda, L., and Grant, G. E.: Sediment transport and channel morphology of small, forested streams, J. Am. Water Resour. Assoc., 41, 853-876, 2005.

Hatten, J. R., Batt, T. R., Scoppettone, G. G., and Dixon, C. J.: An Ecohydraulic Model to Identify and Monitor Moapa Dace Habitat, PLOS ONE, 8, e55551, 2013.

Hawkins, D. K. and Quinn, T. P.: Critical swimming velocity and associated morphology of juvenile coastal cutthroat trout (Oncorhynchus clarki clarki), steelhead trout (Oncorhynchus mykiss), and their hybrids, Canadian Journal of Fisheries and Aquatic Sciences, 53, 1487-1496, 1996.

He, Z., Wu, W., and Shields, F. D., Jr.: Numerical analysis of effects of large wood structures on channel morphology and fish habitat suitability in a Southern US sandy creek, Ecohydrology, 2, 370-380, 2009.

House, R. A. and Boehne, P. L.: Effects of Instream Structures on Salmonid Habitat and Populations in Tobe Creek, Oregon, North American Journal of Fisheries Management, 6, 38-46, 1986.

Huusko, A., Greenberg, L., Stickler, M., Linnansaari, T., Nykanen, M., Vehanen, T., Koljonen, S., Louhi, P., and Alfredsen, K.: Life in the ice lane: The winter ecology of stream salmonids, River Research and Applications, 23, 469-491, 2007.

Jang, C.-L. and Shimizu, Y.: Numerical Simulation of Relatively Wide, Shallow Channels with Erodible Banks, Journal of Hydraulic Engineering, 131, 565-575, 2005.

Jeffres, C. A., Opperman, J. J., and Moyle, P. B.: Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river, Environmental Biology of Fishes, 83, 449-458, 2008.

Johnson, S. L., Rodgers, J. D., Solazzi, M. F., and Nickelson, T. E.: Effects of an increase in large wood on abundance and survival of juvenile salmonids (Oncorhynchus spp.) in an Oregon coastal stream, Canadian Journal of Fisheries and Aquatic Sciences, 62, 412-424, 2005.

Jones, K. K., Anlauf-Dunn, K., Jacobsen, P. S., Strickland, M., Tennant, L., and Tippery, S. E.: Effectiveness of Instream Wood Treatments to Restore Stream Complexity and Winter Rearing Habitat for Juvenile Coho Salmon, Transactions of the American Fisheries Society, 143, 334-345, 2014.

Kafle, M. and Shakya, N.: Two-Dimensional Hydrodynamic Modelling of Koshi River and Prediction of Inundation Parameters. , Hydrology: Current Research, 9, 2018.

Katz, S. B., Segura, C., and Warren, D. R.: The influence of channel bed disturbance on benthic Chlorophyll a: A high resolution perspective, Geomorphology, 305, 141-153, 2018.

Kean, J. W. and Smith, J. D.: Form drag in rivers due to small-scale natural topographic features: 1. Regular sequences, Journal of Geophysical Research: Earth Surface, 111, n/a-n/a, 2006.

Laliberte, J. J., Post, J. R., and Rosenfeld, J. S.: Hydraulic geometry and longitudinal patterns of habitat quantity and quality for rainbow trout (Oncorhynchus mykiss), River Research and Applications, 30, 593-601, 2014.

Lee, J. H., Kil, J. T., and Jeong, S.: Evaluation of physical fish habitat quality enhancement designs in urban streams using a 2D hydrodynamic model, Ecological Engineering, 36, 1251-1259, 2010.

Lisle, T. E.: Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California, GSA Bulletin, 97, 999-1011, 1986.

Lisle, T. E. and Lewis, J.: Effects of sediment transport on survival of salmonid embryos in a natural stream - A simulation approach, Canadian Journal of Fisheries and Aquatic Sciences, 49, 2337-2344, 1992.

Lisle, T. E., Nelson, J. M., Pitlick, J., Madej, M. A., and Barkett, B. L.: Variability of bed mobility in natural, gravel-bed channels and adjustments to sediment load at local and reach scales, Water Resour. Res., 36, 3743–3755, 2000.

McMahon, T. E. and Hartman, G. F.: Influence of Cover Complexity and Current Velocity on Winter Habitat Use by Juvenile Coho Salmon (Oncorhynchus kisutch), Canadian Journal of Fisheries and Aquatic Sciences, 46, 1551-1557, 1989.

Merten, E., Finlay, J., Johnson, L., Newman, R., Stefan, H., and Vondracek, B.: Factors influencing wood mobilization in streams, Water Resour. Res., 46, n/a-n/a, 2010.

Montgomery, D. R. and Buffington, J. M.: Channel-reach morphology in mountain drainage basins, Geological Society of America Bulletin, 109, 596-611, 1997.

Montgomery, D. R., Buffington, J. M., Smith, R. D., Schmidt, K. M., and Pess, G.: Pool Spacing in Forest Channels, Water Resour. Res., 31, 1097-1105, 1995.

Mueller, E. R. and Pitlick, J.: Sediment supply and channel morphology in mountain river systems: 2. Single thread to braided transitions, Journal of Geophysical Research-Earth Surface, 119, 1516-1541, 2014.

Mueller, E. R., Pitlick, J., and Nelson, J. M.: Variation in the reference shields stress for bed load transport in gravel-bed streams and rivers, Water Resour. Res., 41, W04006, 2005.

Mutz, M., Kalbus, E., and Meinecke, S.: Effect of instream wood on vertical water flux in low-energy sand bed flume experiments, Water Resour. Res., 43, n/a-n/a, 2007.

Nagaya, T., Shiraishi, Y., Onitsuka, K., Higashino, M., Takami, T., Otsuka, N., Akiyama, J., and Ozeki, H.: Evaluation of suitable hydraulic conditions for spawning of ayu with horizontal 2D numerical simulation and PHABSIM, Ecological Modelling, 215, 133-143, 2008.

5 Nelson, J. M., Shimizu, Y., Abe, T., Asahi, K., Gamou, M., Inoue, T., Iwasaki, T., Kakinuma, T., Kawamura, S., Kimura, I., Kyuka, T., McDonald, R. R., Nabi, M., Nakatsugawa, M., Simões, F. R., Takebayashi, H., and Watanabe, Y.: The international river interface cooperative: Public domain flow and morphodynamics software for education and applications, Advances in Water Resources, 93, 62-74, 2016.

10 Nicholas, A. P.: Investigation of spatially distributed braided river flows using a two-dimensional hydraulic model, Earth Surface Processes and Landforms, 28, 655-674, 2003.

Nickelson, T. E. and Lawson, P. W.: Population viability of coho salmon, Oncorhynchus kisutch, in Oregon coastal basins: application of a habitat-based life cycle model, Canadian Journal of Fisheries and Aquatic Sciences, 55, 2383-2392, 1998.

Nickelson, T. E., Rodgers, J. D., Johnson, S. L., and Solazzi, M. F.: Seasonal-changes in habitat use by juvenile coho salmon (Oncorhynchus-
15 kisutch) in Oregon Coastal Streams, Canadian Journal of Fisheries and Aquatic Sciences, 49, 783-789, 1992a.

Nickelson, T. E., Solazzi, M. F., Johnson, S. L., and Rodgers, J. D.: Effectiveness of Selected Stream Improvement Techniques to Create Suitable Summer and Winter Rearing Habitat for Juvenile Coho Salmon (Oncorhynchus kisutch) in Oregon Coastal Streams, Canadian Journal of Fisheries and Aquatic Sciences, 49, 790-794, 1992b.

NMFS: (National Marine Fisheries Service) Recovery Plan for Oregon Coast CohoSalmon Evolutionarily Significant Unit, National Marine
20 Fisheries Service, West Coast Region, Portland, Oregon, 2016.

Paola, C.: Incoherent structures: turbulence as a metaphor for stream braiding. In: Coherent Flow Structures in Open Channels, Ashworth, P. J., Bennett, S.J., Best, J.L.,McLelland, S.J. (Ed.), John Wiley & Sons, Ltd, Chichester,, 1996.

Pess, G. R., Liermann, M. C., McHenry, M. L., Peters, R. J., and Bennett, T. R.: Juvenile salmon response to the placement of engineered log jams (eljs) in the Elwha River,Washington State, USA, River Research and Applications, 28, 872-881, 2012.

25 Quinn, T. P. and Peterson, N. P.: The influence of habitat complexity and fish sire on over-winter survival and growth of individually marked juvenile coho salmon (Oncorhynchus kisutch) in Big Beef creek, Washington, Canadian Journal of Fisheries and Aquatic Sciences, 53, 1555-1564, 1996.

Rimmer, D. M., Paim, U., and Saunders, R. L.: Autumnal Habitat Shift of Juvenile Atlantic Salmon (Salmo salar) in a Small River, Canadian Journal of Fisheries and Aquatic Sciences, 40, 671-680, 1983.

30 Roni, P., Beechie, T., Pess, G., and Hanson, K.: Wood placement in river restoration: fact, fiction, and future direction, Canadian Journal of Fisheries and Aquatic Sciences, 72, 466-478, 2014.

Roni, P., Hanson, K., and Beechie, T.: Global review of the physical and biological effectiveness of stream habitat rehabilitation techniques, North American Journal of Fisheries Management, 28, 856-890, 2008.

Roni, P. and Quinn, T. P.: Density and size of juvenile salmonids in response to placement of large woody debris in western Oregon and
35 Washington streams, Canadian Journal of Fisheries and Aquatic Sciences, 58, 282-292, 2001.

Rosenberger, A. E. and Dunham, J. B.: Validation of Abundance Estimates from Mark–Recapture and Removal Techniques for Rainbow Trout Captured by Electrofishing in Small Streams, North American Journal of Fisheries Management, 25, 1395-1410, 2005.

Ruiz-Villanueva, V., Wyżga, B., Zawiejska, J., Hajdukiewicz, M., and Stoffel, M.: Factors controlling large-wood transport in a mountain river, Geomorphology, 272, 21-31, 2016.

40 Ruiz Villanueva, V., Bladé Castellet, E., Díez-Herrero, A., Bodoque, J. M., and Sánchez-Juny, M.: Two-dimensional modelling of large wood transport during flash floods, Earth Surface Processes and Landforms, 39, 438-449, 2014.

Scheingross, J. S., Winchell, E. W., Lamb, M. P., and Dietrich, W. E.: Influence of bed patchiness, slope, grain hiding, and form drag on gravel mobilization in very steep streams, Journal of Geophysical Research-Earth Surface, 118, 982-1001, 2013.

Sedell, J. R., Bisson, P. A., Swanson, F. J., and Gregory, S. V.: What we know about large trees that fall into streams and rivers. In: From
45 the forest to the sea: a story of fallen trees, Maser, C., Tarrant, R. F., Trappe, J. M., and Franklin, J. F. (Eds.), U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; U.S. Department of the Interior, Bureau of Land Management, Portland, OR, 1988.

Segura, C. and Pitlick, J.: Coupling fluvial-hydraulic models to predict gravel transport in spatially variable flows, Journal of Geophysical Research: Earth Surface, doi: 10.1002/2014JF003302, 2015. 2015.

50 Seo, J. I., Nakamura, F., Nakano, D., Ichiyanagi, H., and Chun, K. W.: Factors controlling the fluvial export of large woody debris, and its contribution to organic carbon budgets at watershed scales, Water Resour. Res., 44, 2008.

Shimizu, T. and Takebayashi, H.: Nays2DH Solver Manual, 1 iRIC Project Japan, 2014.

Smith, S. M. and Prestegaard, K. L.: Hydraulic performance of a morphology-based stream channel design, Water Resour. Res., 41, n/a-n/a, 2005.

55 Sommer, T. R., Nobriga, M. L., Harrell, W. C., Batham, W., and Kimmerer, W. J.: Floodplain rearing of juvenile chinook salmon: evidence of enhanced growth and survival, Canadian Journal of Fisheries and Aquatic Sciences, 58, 325-333, 2001.

Stednick, J. D.: Hydrological and biological responses to forest practices : the Alsea Watershed study, Springer, New York, 2008.

Suring, E., R.J., C., Lorion, C. M., Miller, B. A., and Wiley, D. J.: Salmonid life cycle monitoring in western Oregon streams, 2009-2011, Monitoring Program Report Number OPSW-ODFW-2012-2. Wildlife, O. D. o. F. a. (Ed.), Salem, OR, 2012.

Swales, S. and Levings, C. D.: Role of Off-Channel Ponds in the Life Cycle of Coho Salmon (Oncorhynchus kisutch) and Other Juvenile Salmonids in the Coldwater River, British Columbia, Canadian Journal of Fisheries and Aquatic Sciences, 46, 232-242, 1989.

Takebayashi, H., Egashira, S., and Okabe, T.: NUMERICAL ANALYSIS OF BRAIDED STREAMS FORMED ON BEDS WITH NON-UNIFORM SEDIMENT, PROCEEDINGS OF HYDRAULIC ENGINEERING, 47, 631-636, 2003.

Tamminga, A. D., Eaton, B. C., and Hugenholtz, C. H.: UAS-based remote sensing of fluvial change following an extreme flood event, Earth Surface Processes and Landforms, 40, 1464-1476, 2015.

Taylor, E. B. and McPhail, J. D.: Variation in Burst and Prolonged Swimming Performance Among British Columbia Populations of Coho Salmon, Oncorhynchus kisutch, Canadian Journal of Fisheries and Aquatic Sciences, 42, 2029-2033, 1985.

Thompson, D. M. and Fixler, S. A.: Formation and maintenance of a forced pool-riffle couplet following loading of large wood, Geomorphology, 296, 74-90, 2017.

Triska, F. J. and Cromack, K., Jr.: The role of wood debris in forests and streams. . In: Forests: fresh perspectives from ecosystem analysis. Proceedings of the 40th Annual Biology Colloquium. , Press, O. S. U. (Ed.), Corvallis, OR, 1980.

Tschaplinski, P. J. and Hartman, G. F.: Winter Distribution of Juvenile Coho Salmon (Oncorhynchus kisutch) Before and After Logging in Carnation Creek, British Columbia, and Some Implications for Overwinter Survival, Canadian Journal of Fisheries and Aquatic Sciences, 40, 452-461, 1983.

Venter, O., Grant, J. W. A., Noël, M. V., and Kim, J.-w.: Mechanisms underlying the increase in young-of-the-year Atlantic salmon (Salmo salar) density with habitat complexity, Canadian Journal of Fisheries and Aquatic Sciences, 65, 1956-1964, 2008.

Wall, C. E., Bouwes, N., Wheaton, J. M., Bennett, S. N., Saunders, W. C., McHugh, P. A., and Jordan, C. E.: Design and monitoring of woody structures and their benefits to juvenile steelhead (Oncorhynchus mykiss) using a net rate of energy intake model, Canadian Journal of Fisheries and Aquatic Sciences, 74, 727-738, 2016.

Whiteway, S. L., Biron, P. M., Zimmermann, A., Venter, O., and Grant, J. W. A.: Do in-stream restoration structures enhance salmonid abundance? A meta-analysis, Canadian Journal of Fisheries and Aquatic Sciences, 67, 831-841, 2010.

Wilcock, P. R. and McArdell, B. W.: Surface-based fractional transport rates - mobilization thresholds and partial transport of a sand-gravel sediment, Water Resour. Res., 29, 1297-1312, 1993.

Wipfli, M. S., Richardson, J. S., and Naiman, R. J.: Ecological linkages between headwaters and downstream ecosystems: Transport of organic matter, invertebrates, and wood down headwater channels, J. Am. Water Resour. Assoc., 43, 72-85, 2007.

Wohl, E. and Jaeger, K.: A conceptual model for the longitudinal distribution of wood in mountain streams, Earth Surface Processes and Landforms, 34, 329-344, 2009.

Wohl, E. and Scott, D. N.: Wood and sediment storage and dynamics in river corridors, Earth Surface Processes and Landforms, 42, 5-23, 2017.

Wolman, M. G.: A method of sampling coarse river bed material, Transactions of the American Geophysical Union, 35, 951–956., 1954.

Yabe, T., Ishikawa, T., Kadota, Y., and Ikeda, F.: A Multidimensional Cubic-Interpolated Pseudoparticle (CIP) Method without Time Splitting Technique for Hyperbolic Equations, Journal of the Physical Society of Japan, 59, 2301-2304, 1990.

Yager, E. M., Kirchner, J. W., and Dietrich, W. E.: Calculating bed load transport in steep boulder bed channels, Water Resour. Res., 43, n/a-n/a, 2007.