Point-by-point response to the reviews,

Reply to Referee #1

The manuscript describes an evaluation of a stream restoration project by large wood introduction in three gravel bed streams in the US. A 2D hydrodynamic model is applied, which had been calibrated with field observations. The calibrated model is then applied to study the habitat suitability for a juvenile salmonid species at bankfull discharge. Large wood increases the size of suitable habitat in all three field sites.
I read this manuscript with a lot of interest. I think the subject is very relevant because large wood introduction is a cost-effective stream restoration method, with a lot of benefits for stream ecology. In general, the manuscript is well written and the figures are well prepared. The Introduction contains most relevant information, the methods are clearly described and the results are well presented, as well.
The main critic I have is that the authors only focus on a single discharge (i.e. bankfull) when presenting the results, while it might not be too difficult to extend the results with other relevant discharge classes as well. When I was reading the Introduction, I had the feeling the authors would go in that direction. On page 2 (lines 22-24) the authors argue that there is a lack of understanding of the effect of large wood on flow conditions under a range of discharges. So why are only results shown for bankfull discharge conditions and not for other conditions? As far as I understand it well, the model was calibrated for several discharge levels (Table 2). So the model calibration would not put limitations for model application at other than bankfull discharge conditions. Furthermore, in this age of abundant computational resources, I would never argue that additional model runs are not possible because of computational costs. Hence, I suggest to extend the results with other relevant discharge conditions to increase the implications of large wood introduction on habitat suitability for the Coho Salmon.

Reply: We appreciate this comment, which was also raised by the other reviewer. Given the Nays2D is unsteady we actually run the model for 35–45 hour long hydrographs that peaked around bankfull but included a wide range of flows in all sites. We made this clearer in the methods (P5, L17–20; P7, 28–30). Based on these simulations we now include a section in the results highlighting changes in simulated habitat availability before and after the addition of LW during the whole hydrograph duration (see section 3.3., Figure 7 and Table 3).

Overall, I think this manuscript has potential to be a valuable addition to the literature, but some works is still required to make it acceptable for publication. Below I have provided general and specific comments to the text.

Reply: We really appreciate your careful review.

General comments

The Introduction is mainly focused on the effect of large wood on streams in the Pacific Northwest (US). In Europe (and most likely also in other continents) wood is also used in stream restoration, which deserves some attention as well. I suggest to at least add some references to studies where wood is used, not only to improve the habitat conditions for fish, but also to improve conditions for macroinvertebrates.

Reply: We appreciate the suggestion. We added a paper about wood in European rivers (Kail, 2003) and two papers about the importance of wood for macroinvertebrates (Gerhard & Reich, 2000; Jahnig & Lorenz, 2008) (P1, L24; P1, L30; P2, L1).

Throughout the manuscript the authors use v and τ to refer to velocity and stress. Sometimes this results in sentences like "...depth-averaged flow v and shear τ ..." (Page 12, line 9), which may be difficult to read for readers without much knowledge in hydraulics. Therefore, I suggest to write "velocity" and "stress" in full where possible.

Reply: We agree. We eliminated most of the "v" and "t" to improve readability throughout the text.

Specific comments

- Page 2, line 34: From "Our objective...". I suggest to start a new paragraph here and first summarize in 1-2 sentences the main limitations of previous research, followed by the objective.

Reply: As suggested, we added a new paragraph clearly stating the limitation of previous efforts before stating our objective (P3, L 11–16).

- Page 3, line 12: It is more common to characterize annual precipitation sum in mm, than in cm.

Reply: Done (P3, L24).

- Page 4, lines 9-11: How was the discharge for the depth-discharge rating curves determined? Through measurements or modelling? Please clarify in the text.

Reply: We added information about how we developed the stage discharge relations: Discharge was measured using the velocity-area method (Dingman, 2002) using a Hack FH950 Portable Velocity meter and depth-discharge rating curves were developed based on 9-10 discharge measurements per site (P4, L13–14).

- Page 6, line 32: How were these flow velocity measurements performed? This is not mentioned in the text, please clarify.

Reply: We have clarified in the text that these 13–24 velocity measurements per site were taken across the stream (Figure 2, Table 2) for 2-3 flow levels (P7, L22).

- Page 8, lines 5-6: The authors mean that the velocity distribution was more homogeneous before LW introduction and more heterogeneous after LW introduction? Please clarify in the text.

Reply: We have added some text clarifying that the velocity distributions were more homogenous before the LW additions (P8, L26).

- Page 9, lines 4-6: I suggest to show the percentage increase or decrease, which is more consistent with the previous sentences.

Reply: The suggested changed was implemented (P9, L15–16).

- Page 10, lines 13-14: The authors refer to Fig. 6, but the spatial changes are shown in Fig. 5.

Reply: Yes, you are correct, thank you (P11, L8)

- Page 10, lines 14-17: These sentences are somewhat confusing. The authors are referring to a number of observations, but do you mean simulation results? Also, the results do depend on the chosen transport threshold, hence, the word “independent” should be “dependent”, right? I also would not use the term “significant” in this context, since most readers associate it with statistical significance. In general, the authors are discussing the results here, maybe better to move this to the Discussion section.

Reply: We agree that these sentences do not belong in the results section. We decided to eliminate them as they do not add much to our findings.

- Page 11, lines 8-11: The fitted gamma parameter values are not shown. I suggest to add these values to each of the panels of Fig. 6.

Reply: We appreciated the suggestion. The values have been added to the figure.

- Page 12, line 7: Please add “in” between “increases” and “the heterogeneity”.

Reply: Done (P14, 4).

- Page 14, lines 2-5: The authors refer here to “small reaches”, do you mean “narrow”? Please clarify in the text.

Reply: We mean small not only in the sense of narrow but also smaller in terms of having less drainage area and thus less discharge. We have clarified this in the text (P16, L21 –22).

Figures and Tables

- Figure 1: I suggest to use some colors to indicate the wood and WSE rulers. Or maybe use a solid black line for the wood, instead of the pattern fill.

Reply: We believe you are referring to figure 2 here. We changed the color of the Wood pieces as suggested.

References mentioned in the reply.

Dingman, S. L. (2002). *Physical hydrology*. Upper Saddle River, N.J.: Prentice Hall.

Gerhard, M., & Reich, M. (2000). 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*(1), 123-137. doi:10.1002/(sici)1522-2632(200003)85:1<123::aid-iroh123>3.3.co;2-k

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Kail, J. (2003). Influence of large woody debris on the morphology of six central European streams. *Geomorphology, 51*(1), 207-223. doi:https://doi.org/10.1016/S0169-555X(02)00337-9

Reply to Anonymous Referee #2

General comments

The manuscript details a study built around stream restoration efforts, and aims to evaluate the effects that large wood placement has on hydraulic habitat for fish. To this end, the authors apply a 2-dimensional hydraulic model, calibrated based on field observations. To assess the relevance of altered channel hydraulics for fish habitat, modeled flow characteristics are linked with empirical information on fish swimming performance and bed material size (to assess its mobility).

I agree with the authors that better understanding of the hydraulic effects that large wood has on stream processes is an important subject. From the basic science point of view, this topic is of interest because large wood is a key driver of many physical and biological processes in river ecosystems. Likewise, this topic is also critical from the applied river science perspective, because large wood placement to enhance fish habitat is, by far, the most common channel restoration activity (at least in the geographical regions I am most familiar with).

The methodology applied in this study seems to be generally robust, although some additional information on model limitations and uncertainties would be desirable, to provide readers with more complete information. Similarly, interpretations and conclusions appear to be supported by the data, but I would encourage the authors to elaborate further on this in the context of model limitations. From the technical point of view, the manuscript is written well and has good quality figures that convey key results effectively. However, the manuscript would benefit from exploring in more depth some “pockets” of relevant literature to better contextualize the results. Below, I expand on all the above concerns in more length and give some suggestions.

Recommendations:

Methodology and interpretations. Numerical modeling of flow around large wood is a highly challenging task and there have been relatively few attempts to resolve such flow field in 3D. Thus, in my view, the 2D approach adopted by the authors can be still considered current research standard (e.g., Hafs et al., 2014; Wall et al., 2016). However, as the authors acknowledge, there are clear issues related to modeling highly complex, 3D flow using depth-averaged model and substantial errors can be expected as some assumptions are violated, at least locally (e.g., Shen and Diplas, 2008). Given the importance of this issue, I think the authors devote too little discussion to this limitation.
I would recommend that the authors discuss how the modeled flow field resembles or deviates from the patterns observed in various field studies (Daniels and Rhoads, 2003; 2004a; 2004b; Manners et al., 2007) or in experimental setting (see references below). What are the key uncertainties in the predicted flow given what we know about 3D flow structure around such obstructions? What are the implications for the predicted hydraulic habitat? After all, fish utilize 3D habitat and can adjust their vertical position in the water column.

While these uncertainties certainly do not constitute a disqualifying problem, in my opinion, they need to be signaled to readers more clearly and in more detail, so that they can more readily formulate their own judgement regarding the results.
It would be also informative to know how much of the changes in flow hydraulics (and habitat) occur in close proximity to large wood, where errors are likely large, and how much in the far field, away from the wood? For example, is there a way to plot errors in velocity (modeled-observed) against distance from wood, to get a sense of the spatial extent of the zone where flow properties are not captured well? For example, (Xu and Liu, 2017) showed that flow field predictions away from large wood may be reasonable even if a simple solid body representation is chosen.

Reply: We appreciate your suggestion and agree. We now acknowledge some of the potential issues associated with 2D modelling of flow around obstacles in the discussion section (P 15, L1-16). We also added that the flow around the LW jams will change over time given channel adjustment and the addition of smaller pieces of wood to the jams over time (P15, 22–26). We indicate how our predictions seem to resemble 3D predictions while acknowledging that we lack information to assess the performance of the model near the LW obstacles. We agree that assessing the model predictions based on multiple velocity measurements taken at different distances from the LW would be very informative, but we lack such data. A detailed assessment of this kind is challenging at the reach scale during winter flows because the reaches are not wadable. The velocity measurements we have were collected at a cross-section per reach (Figure 2) 7–20 meters away from the LW additions. We have added to figure 2 the cross-sections in which we collected the velocity measurements.

Literature. The authors generally did a good job presenting most relevant literature but I feel that it is slightly less comprehensive on the numerical modeling side. Because modeling is at the core of this paper, I think the paper would benefit from exploring this literature both for providing background to the reader and for contextualizing the results. Allen and Smith (2012) and (Xu and Liu 2016; 2017) are examples of good recent references to cutting-edge approaches to tackle the challenge of modeling flow near complex features like large wood. In addition, hydraulics of large wood, and particularly engineered log jams (which tend to have simple geometry) bear some similarities to flow around abutments and spur dikes. These parallels have been widely recognized and utilized in the geomorphic literature, e.g. see Abbe and Montgomery (1996) or Buffington et al. (2002). This kind of flow obstructions has been extensively modeled using CFD and engineering literature can serve as a rich source to draw upon in research on large wood; such modeling efforts have also been carried out by river scientists studying restoration structures such as deflectors – see work of Biron and colleagues (Biron et al. 2009; 2012).

Reply: We appreciate the suggestion a paragraph was added to the introduction (P2, L27–33) providing background about the use of CFD models to simulate flow filed conditions around wood.

Uncertainties. The authors should be commended for evaluating model performance on a number of occasions. I think it may be useful to provide more information about this important step of CFD model application. For example, I suggest that the authors consider providing information on the number of measurements used for evaluation (e.g., number of velocity measurements) and the slopes of the regression lines. The latter might be relevant, because bias in modeled velocity, relative to observed velocity, can lead to over- or underestimated heterogeneity in the modeled flow field. For example, if the slope in a modeled conditions prior to wood

placement is 0.6 and, after large wood placement is 0.8, this needs to be taken into account when comparing the differences in complexity of flow field due to large wood placement.
I even wonder if it may make sense to carry out a separate comparison based on field data alone and then another one based on the modeled data, and see if those two results converge; of course, this is only if there are enough data to run reasonable regressions based on field data alone. I also noted that the reported velocity errors seem much higher than those for WSE, which should also be highlighted in the discussion, since velocity affects both aspects of habitat that are of interest here (bed shear stress is a function of velocity squared). The errors are within the range reported in the literature, so the magnitude of errors itself is not alarming, but this issue should be communicated clearly in the text. Also, personally I find that showing the data graphically is often as informative as reporting statistics (or more). I leave it to the authors to decide on the most appropriate course of action.

Reply: The number of observations of water surface elevation and velocity used to evaluate model performance and the slope of the water surface before and after the wood placement were added to Table 2. The calculated WSE slopes are within 10% of the observed slopes indicating strong performance of the model. The velocity observations pre and post wood were used as an additional check. However, given how difficult (dangerous) it is to collect velocity measurements at high flows our calibration relied strongly in the WSE observations. We clarified this in the methods (P7, L20–22) and in the discussion (P15, L12–16). We found that that the mean WSE slopes are higher post wood than pre wood. This change in slope is a reflection of the effects of the wood in the flow field (P9, L1; P11, L10–11; P15, 32–34).

<u>Flow event choice</u>. Lastly, I would recommend that the authors further clarify the ecological relevance of bankfull flow for answering their research question. Why was it chosen for this paper out of a wide range of discharges a rainfall-dominated stream may experience during the winter season? Of course, this does seem like an intuitive choice for bed mobility modeling. However, it is slightly less clear why that would be the key flow for fish. Bankfull flow in wet coastal streams in Oregon has, on average, recurrence interval of ~1.2 years (Castro and Jackson 2001) and in pluvial hydrological regime flows in excess of that discharge probably last a few days per year. If bankfull flow is critical because of limited flow refugia, or was chosen because of its relevance for sediment transport and because changes in habitat patterns at lower discharges are similar, that should be clearly conveyed in the manuscript. I think it is important for readers to be able to understand broader importance of the reported results, how they extend beyond just a single flow event.

Reply: We appreciate this comment, which was also raised by the other reviewer. Given the Nays2D is unsteady we actually run the model for 35–45 hour long hydrographs that peaked around bankfull but included a wide range of flows in all sites. We made this clearer in the methods (P7, L28–30). Based on these simulations we now include a section in the results highlighting changes in simulated habitat availability before and after the addition of LW during the whole hydrograph duration (see section 3.3., Figure 7 and Table 3).

Minor comments & suggestions:

p. 1, line 25-27: LW also influences bed texture – consider citing work of (Buffington and Montgomery 1999).

Reply: We added this reference to the introduction (P1, L25).

p. 2, line 5-7: interesting work on LW removal effects by R.D. Smith and colleagues (Smith et al. 1993a, 1993b)

Reply: We agree, we have added these references (P2, L8).

p. 2, line 8-12: I think the clarity of this paragraph would be improved if the authors added a sentence that stated clearly that low velocity habitat is critical for overwinter juvenile survival. This is perhaps a minor point but for the readership of ESD not familiar with fish ecology can be helpful in following the logical flow of this argument (overwinter survival of juveniles key for population viability & low velocity important for juvenile survival => low velocity habitat critical for population recovery).

Reply: We appreciate this suggestion and the paragraph has been edited throughout to improve clarity and logical flow (P2, L9–16).

p. 2, line 16: work of Sommer et al. and Jeffres et al., while undoubtedly interesting and relevant, should be cited with caution in this context, since it was conducted on a very different river system in different climate (floodplains of larger rivers in California Central Valley).

Reply: We agree with you. We decided to remove these two references.

p. 2, line 31-34: I want to point out excellent work by A. Finstad and colleagues on the importance of bed shelters for salmonids, although, of course, there may be some differences between Atlantic salmon and Coho (Finstad et al. 2007; 2009)

Reply: We appreciate this suggestion, but the work by Finstad and colleagues on Atlantic Salmon does not directly translate to Coho Salmon, which are not as strongly associated with the substrate during normal winter flows, therefore we did not add these references.

p. 3, line 12: suggest reporting in units of mm or m, not cm.

Reply: Done, (P3, L24).

p. 3, line 14: how, specifically, are the study reaches geomorphically distinct? Please clarify Table 1: what is bankfull area?

Reply: We change this sentence eliminating the notion that the reaches are located in distinct geomorphology. The most relevant point here is they are all low gradient and fish bearing (P3, L25). Bank full area is the cross-sectional area at bankfull level. We added the word cross-sectional (Table 1) in an effort to make this clearer.

p. 6, line 20: the equation (3) defines Cf parameter, then text (e.g., line 27 on that page) refers to Cd – are those the same? Or is this just a typo? Please fix or clarify.

Reply: Yes that was a typo thank you (P7, L15)

p. 7, line 1-3: given that large wood is at the heart of this study, it actually would be interesting to evaluate also flow field around wood. Once again, poor performance in those areas is to be expected and, in my view, does not disqualify this or any other similar work using 2D, given very limited alternatives, but it would be informative to know the magnitude of errors an spatial extent of the zone within which flow parameters are not modeled reliably. For example, one could evaluate model prediction near and away from LW, or compare evaluations including and excluding near-LW data points.

Reply: Agreed that this would be an interesting line of inquiry, unfortunately, we do not have the velocity measurement data to look into this and through calibration. We clarified this in the methods (P7, L20–21) and in the discussion (P15, L12–16).

p.7, line 7: depth threshold of 0.1m seems somewhat high for juvenile Coho (they can certainly swim in shallower flows). But perhaps there is also another reason/criterion why this cutoff was chosen?

Reply: While juvenile Coho can certainly swim in very shallow areas, they are seldom found in water less than 0.1 m deep during the winter (Bustard and Narver 1975a). The text was edited to clarify this point, and the reference above was added to the text (P8, L1).

p. 9, line 12: perhaps “robustness” not “resiliency”?

Reply: We agree the changed was made (P10, L1).

p. 11, line 9: could the authors clarify whether/how gamma distribution was fitted in cases of bimodal data?

Reply: We follow the methodology describe in (Segura & Pitlick, 2015). The parameters of the gamma function that best fitted the distributions were found by systematically varying the α parameter between 0 and 60 in increments of 0.01 (i.e., total 6000 α values tested) and finding the parameter values that yielded the lowest overall χ 2 score. We added the mention reference. Given that we are trying to make predictions based in this fits but rather to illustrate the changes in shape of distributions of shear stress we believe there is no need to provide more details here. However, here is a figure of the fits for your review.

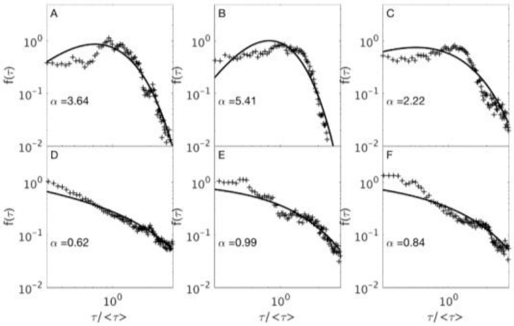

Figure R1: Gamma fits to the distributions of shear stress before (A-C) and after (D-F) the additions of LW in sites 1 (A,D), Site 2(B,E) and site 3 (C,F).

p. 12, line 4 (and elsewhere): I would encourage the authors to refer to “modeled” or “simulated” habitat rather than habitat. This may seem like hairsplitting but I think it would be prudent to emphasize that these are model predictions rather than empirical data.

Reply: We agree. We made changes accordingly.

p. 15, line 8: “processed” not “process”

Reply: The wording was changed (P17, L22–23)

Throughout the paper, the authors use v and u for downstream and cross-stream components of the velocity vector (e.g. equation (1) but later v also comes up to describe swimming velocity criteria for fish. The authors should be careful here to avoid using the same symbol for different variables – please fix or clarify.

Reply: We agree, we changed the notation for the cross-stream velocity component (P6, L26)

In sum, I want to emphasize once again that I believe that, upon revisions, this manuscript could be a valuable contribution to the literature. It focuses on important subject within the field of ecgeomorphology and the methodological approach it adopts, despite some limitations, is scientifically defensible and in line with current research practice. As a result, I believe the reported results are robust and will be of interest to the readership, especially researchers interested in topics at the intersection of earth surface processes and ecology. I look forward to seeing authors’ responses as well as the revised manuscript.

Reply: We really appreciate your careful and thoughtful review.

References

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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 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 and shear stress 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 ~~τ~~ shear stress required to mobilize the median bed particle size. Model predictions indicated that survivable habitat during bankfull conditions, measured as the area with velocity~~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 shear stress ~~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 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; Montgomery et al., 1995; Kail, 2003). LW structures increase heterogeneity in the flow field by promoting local scour and sediment retention, by reducing average flow velocity, by influencing bed texture (Buffington and Montgomery, 1999a), 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 bars, and riffles), offering a wide range of habitat for aquatic species including invertebrates and fish (Fausch and Northcote, 1992; Gerhard and Reich, 2000; Roni and Quinn, 2001; Dolloff and Warren, 2003; Jahnig and Lorenz, 2008; 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 of stream complexity (Bisson et al., 1987; Sedell et al., 1988; Stednick, 2008), which has reduced habitat and ~~c~~contributed~~ing~~ to fish population declines (Dolloff, 1986; House and Boehne, 1986; Fausch and Northcote, 1992; Smith et al., 1993a; Smith et al., 1993b; Brown et al., 1994).

For Coho Salmon, which generally spend at least one year rearing in freshwater prior to out-migration to the ocean, ~~Within the freshwater habitat,~~ overwinter survival ~~for juvenile Coho Salmon~~ has been identified as a critical factor influencing ~~critical aspect for~~ population abundance and productivity (Tschaplinski and Hartman, 1983; Nickelson et al., 1992a; Nickelson et al., 1992b; Quinn and Peterson, 1996; Huusko et al., 2007; Gallagher et al., 2012; Suring et al., 2012). ~~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).~~ Coho Salmon overwinter survival is strongly linked to the availability of complex, low velocity habitats that have been reduced in many areas due to land use and development (Tschaplinski and Hartman, 1983; McMahon and Hartman, 1989; Quinn and Peterson, 1996; Johnson et al., 2005). Thus, restoration of ~~increases in low velocity~~ winter refuge habitat for Coho Salmon can be crucial~~refuge may be critical for species~~ for population viability and species recovery ~~recovery~~ (Nickelson and Lawson, 1998; 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 ~~{Tschaplinski, 1983 #4592}~~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). 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.

Previous efforts have used computational fluid dynamics models to simulate field conditions around obstacles such as wood and boulders in theoretical domains (Allen and Smith 2012) and experiment flumes (Xu and Liu, 2016; Lai et al., 2017; Xu and Liu, 2017) in some cases using flow deflectors to mimic the effects of wood in channels (Biron et al., 2009). These studies have provided detailed descriptions of the turbulent flow around these structures, highlighting the effects of simplifying the geometry of the obstacles in the prediction of flow velocity (Allen and Smith 2012; Xu and Liu, 2017), and the effects of the assumed obstacle shape and orientation on the velocity field and sediment transport (Biron et al., 2009; Biron et al., 2012). However, these models are computational intensive and not yet feasible at the reach scale.

Two-dimensional (2D) c~~C~~omputational hydraulic modelling offers a relatively time and cost-effective strategy to ~~analyze~~analyse the flow field of a stream reach without the need for high-resolution field measurements at every discharge level of interest. These 2D ~~wo-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) including the ~~but studies directly addressing the~~ effects of ~~LW pieces or other~~ boulders ~~flow obstacles in the flow field have been limited~~ in ~~to~~ straight urban sections (Lee et al., 2010) and the effects of large wood using ~~or~~ non-calibrated models (Hafs et al., 2014; Wall et al., 2016). The 2D estimates 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.

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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 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 2,300 m~~c~~m 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 different tributaries: ~~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 Cerine Creek, and Site 3 is located in the South Fork (Table 1). All sites display low to moderately developed pool riffle sequences with bankfull discharge (Q_{bf}) between 2.4 and 8.7 m^3/s (Table 1).

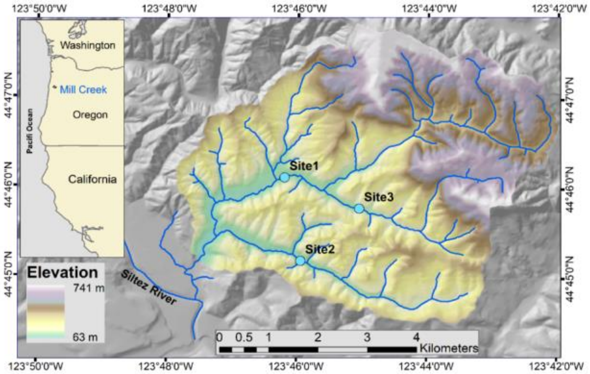


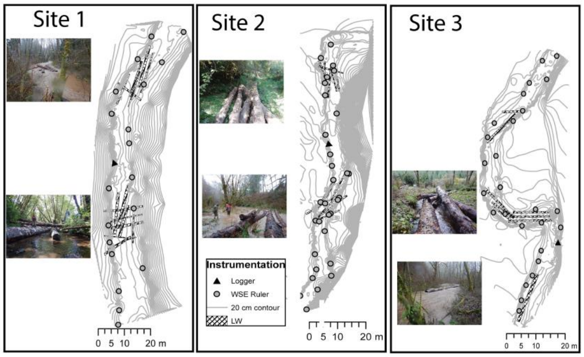
Figure 1. Location of the Mill Creek watershed, OR and the Study Sites 1, 2, and 3.

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	km^2	16	5	5
Length	m	119	123	115
Bankfull discharge (Q_{bf})	m^3/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 cross-sectional area	m^2	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/m^2	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, 1999b; 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). Discharge was measured using the velocity-area method (Dingman, 2002) using a Hack FH950 Portable Velocity meter ~~Meter~~ and depth-~~- and developed depth~~ discharge rating curves were developed based on ~~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.



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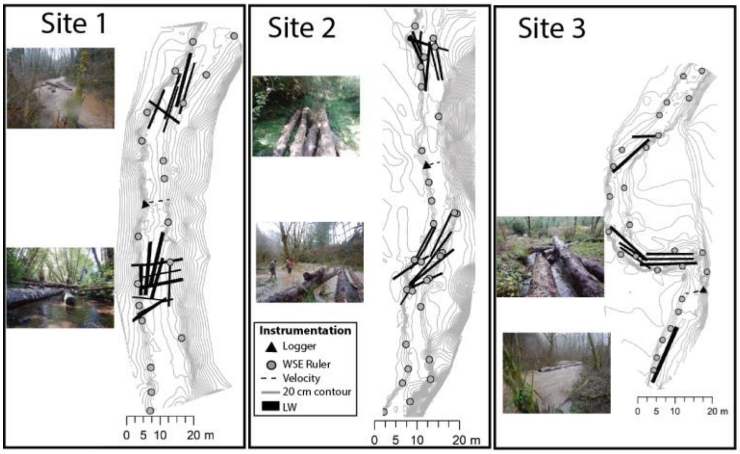

Figure 2. Topography (derived 0.2 m contours) and location of introduced large wood (LW), water surface elevation (WSE) monitoring rulers (circles), ~~and~~ water level loggers (triangle), and location of velocity measurements (dash line). Flow direction is from top to bottom in all three sites.

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 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 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 unsteady models were used to characterize the distributions of depth, velocity, and shear stress pre- and post-LW addition (Table 2) and include a wide range of flows between 0.1 Q_{bf} and Q_{bf}. 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 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).

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Table 2. Nays2DH model parameters and calibration results for pre and post large wood (LW) models for different discharge (Q_i) levels. Fractional bankfull discharge (Q_i/Q_{bf}); average model depth (Hmean); number of water surface elevation (WSE) and velocity (U) observations taken, root mean squared error (RMSE)~~;~~, ~~and~~ R^2 for WSE~~water surface elevation (WSE)~~ and time average ~~velocity (~~U~~)~~ ~~measurements~~ are indicated for calibration runs when available along with observed and modeled WSE slopes.

Site	LW	Q_i (m^3/s)	Q_i $/Q_{bf}$	# Nodes	H_{mean} (m)	# WSE obs.	# U obs.	RMSE-WSE (m)	RMSE-U (m/s)	R^2 WSE	R^2 U	WSE Slope obs. (%)	WSE Slope Modeled (%)
1[a]	pre	4.53	0.52	60621	0.55	15	24	0.025	0.34	0.97	0.41	0.29	0.29
1[a]	pre	8.7	1.00	60621	0.71	15	-	0.0322~~3~~	NA	0.94	NA	0.35	0.37
1[a]	post	1.91	0.22	60621	0.57	13	19	0.078	0.16	0.94	0.39	0.75	0.76
1[b]	post	12	1.38	60621	0.98	6	-	0.2122~~1~~	NA	0.66	NA	0.86	0.89
2[a]	pre	1	0.41	58176	0.421	24	13	0.025	0.122~~15~~	0.97	0.87	0.42	0.41
2[a]	pre	2.43	1.00	58176	0.56	24	16	0.026	0.26~~115~~	0.97	0.87	0.39	0.43
2[a]	post	1.49	0.61	58176	0.53	25	20	0.0349~~9~~	0.26~~49~~	0.98	0.68~~75~~	0.66	0.68
2[b]	post	3.8	1.56	58176	0.58	10	-	0.0855~~3~~	NA	0.90	NA	0.51	0.47
3[a]	pre	1.08	0.49	53169	0.34	26	17	0.045	0.26~~58~~	0.98	0.70	0.88	0.86
3[a]	pre	2.2	1.00	53169	0.46	22	24	0.023	0.36~~4~~	1.00	0.70	0.87	0.85
3[a]	post	1.09	0.50	53169	0.55	24	24	0.036~~7~~	0.26~~9~~	0.99	0.69	1.16	1.15
3[b]	post	3.5	1.59	53169	0.58	11	-	0.134	NA	0.96	NA	1.12	1.17

[a] assuming a constant downstream water surface elevation as the initial boundary condition

[b] uniform flow assumption as the initial upstream and downstream boundary condition

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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 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 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~~w) 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):

$$\tau = \rho C_f (u^2 + w\cancel{v}^2) \qquad (1)$$

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

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

$$C_f = \frac{n^2 g}{h^{1/3}} \qquad (3)$$

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 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 $C_{f\cancel{d}}$ by changing n. The root mean squared error for the WSE, ~~-~~computed based on 6–26 observations per flow, was below 0.~~05~~ 045 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 alter~~ed~~ the observed WSE but were not reflected in our models. For 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 (Table 2). Velocity observations were used as an additional check~~-~~ ~~were also use for~~ after 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) based on 13–24 observations taken across the streams (Fig. 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, 2015a; Katz et al., 2018).

2.4 Data analysis

We evaluated the changes in velocity and shear stress ~~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 during bankfull flow and during the duration of a complete hydrograph in which discharge varied between 0.1Q_{bf} and Q_{bf}. For both velocity and shear stress~~τ~~ distributions, only areas where depth > 0.1 m and velocity or shear stress ~~τ~~ > 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 juvenile fish were likely ~~could~~ to be found (Bustard and Narver, 1975b). We estimated the area with acceptable fish habitat within the modelled domains using a 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~~often shelter in substrate during harsh environmental conditions (Hartman, 1965; Rimmer et al., 1983; Bradford et al., 1995; Cunjak, 1996; Bradford and Higgins, 2001), we used the predicted shear stress ~~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 of the D_{50} was estimated based on slope (s) (Mueller et al., 2005):

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

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

where τ_c^* is the dimensionless critical Shield's stress and ρ_s is sediment density (i.e., 2,500 kg/m^3 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 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 velocity ~~v~~ ranged between 0.53 m/s and 0.92 m/s (Table 3), corresponding to 23.2–36.3% decreases. The distributions of velocity ~~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 velocity~~v~~ distributions were relatively homogenous with ~~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 velocity ~~v~~ values around the mean and a greater proportion of areas in the channel bed that experienced extreme (low and high) velocity ~~v~~ conditions (Fig. 3 and 4). The increased heterogeneity of flow conditions after the LW additions 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. The decrease flow area around the wood is consistent with the increase in the mean WSE slope between pre- and post-LW in all sites (Table 2).

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-LW; and percentage change in available fish habitat.

	Site 1		Site 2		Site 3	
Metric	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						
$v \leq v_{crit}{}^{a}$	15.3	32.5	26.7	52.2	23.8	47.3
$v_{crit} \leq v \leq v_{burst}{}^{a}$	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						
$v \leq v_{crit}{}^{a}$	+112.8%		+95%		+99.3%	
$v_{crit} \leq v \leq v_{burst}{}^{a}$	+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

$^{b}\tau_c$ is the critical shear stress for the movement of the median grain size (Table 1)

The predicted r~~R~~educed velocity ~~v~~ in the stream channels after the addition of LW indicated ~~predicted~~ increased fish habitat in all sites. The proportion of the wetted channel area with velocity ~~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 velocity ~~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 ($v_{cirt} \le v \le v_{burst}$) also increased ~~in sites 1 and 3~~ by 134.5% in Site 1 and by 66.1% in Site 3 ~~from 13.9% and 17.0 % to 32.7% and 28.3%~~ of their 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 $v < v_{busrt}$ prior to the LW introductions (light blue in Fig. 3) and therefore less potential for an increase in that category. These ~~observations~~ predictions clearly indicate that the LW additions increased the area of habitat acceptable for juvenile salmon at Q_{bf}.

As mentioned above, the velocity~~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~~ robustness 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.

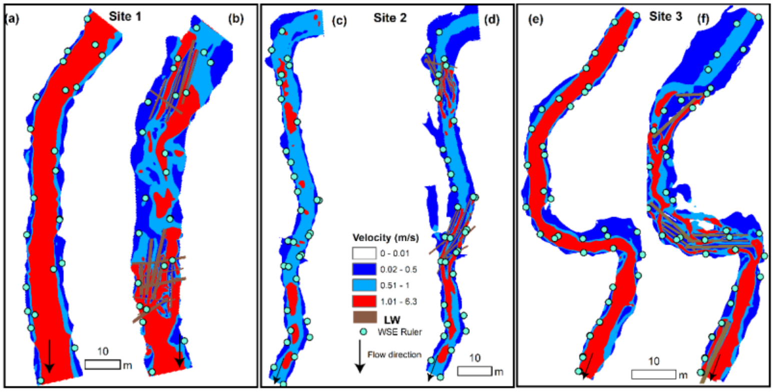


Figure 3. Mean flow velocity at bankfull discharge before (a, c, and e) and after (b, d, and f) the addition of large wood (LW) in Sites 1, 2, and 3. The colors correspond to thresholds of velocity relevant to the ability of juvenile Coho Salmon to maintain position in the stream: dark blue means $v < v_{crit}$ 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 increase extend of floodplain inundation in each site during bankfull conditions.

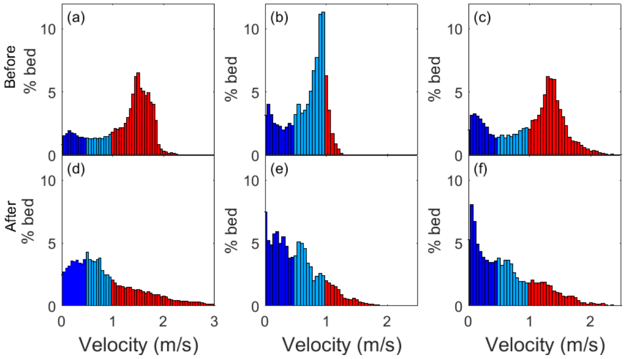


Figure 4. Velocity distributions at bankfull flow at Sites 1 (a, d), 2 (b, e) and 3 (c, f) before (a-c) and after (d-f) the addition of large wood (LW). The colors correspond to thresholds of velocity relevant to the ability of juvenile Coho Salmon to maintain position in the stream: dark blue means $v < v_{crit}$ 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/m^2 in Site 1, 12.24 N/m^2 in Site 2, and 22.27 N/m^2 in Site 3 (Table 3). Modelling results indicated ~~These values decreased~~ 18–49% reductions in shear stress 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 shear stress~~τ~~ were associated with consistent decreases in flow velocity~~v~~ near the channel margins and additional stream connectivity with available floodplains (Fig. ~~6~~5). Additionally, increased WSE slope through the reaches after the addition of LW helped drive the variation in shear stress through the formation of deeper pools upstream of LW jams. ~~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%.~~

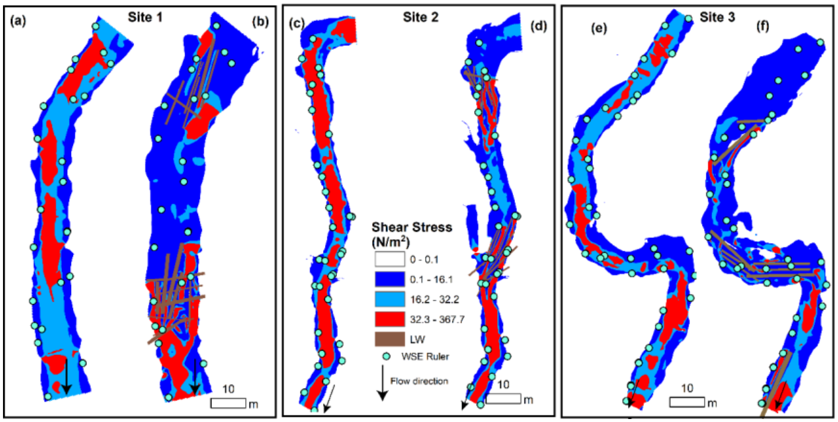
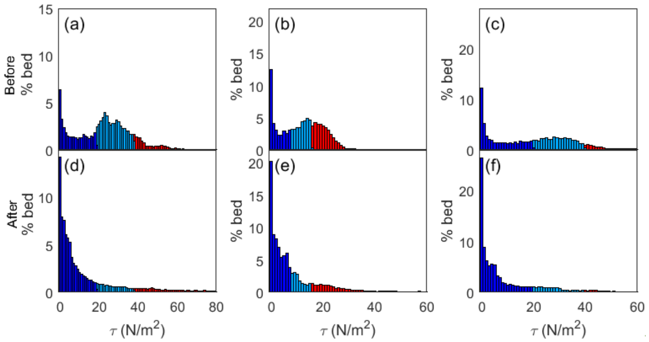


Figure 5. Spatial distributions of shear stress (τ) at bankfull discharge before (a, c, and e) and after (b, d, and f) the addition of large wood (LW). Dark blue corresponds to $\tau < \tau_c$, light blue corresponds to $\tau_c < \tau < 2\tau_c$, and red corresponds to $\tau > 2\tau_c$. The location 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 shear stress ~~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 shear stress ~~τ~~ before and after the LW additions to a gamma function (Segura and Pitlick, 2015b) and found that the shape parameter (α) of the distributions decreased for all sites. While this parameter before LW varied between 2.2 and ~~3.6~~5.4 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.



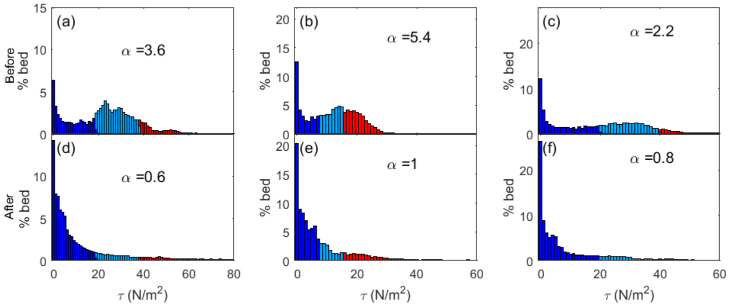


Figure 6. Shear Stress (τ) distributions at bankfull flow at sites 1 (a, d), 2 (b, e) and 3 (c, f) before (a-c) and after (d-f) the addition of large wood (LW). Alpha (α) paramters of the a gamma fit are provided.~~-~~ Dark blue corresponds to $\tau < \tau_c$, light blue corresponds to $\tau_c < \tau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

3.3. Temporal variability in available habitat during full bankfull flow events

Modelled results before LW additions during the entire hydrographs indicated that the reach area with acceptable habitat in terms of velocity ($v < v_{crit}$) varied between 15~~4~~% and 36% in Site 1, 27~~6~~ % and 74% in Site 2~~-~~, and 23~~2~~% and 38~~7~~% in Site 3 (Table 4, Fig. 7 a–c). These percentages of reach area with acceptable habitat increased after the addition of LW to 31–74% in Site 1, 48–85% in Site 2, and 4~~7~~2–72% in Site 3 (Fig.~~gure~~ 7 a–c) indicating average increases between 2~~2-~~3 % and 29 % (Table 4~~3~~ and Fig. 7 a–c). The temporal variability in the percentage of the channel with acceptable habitat ($v < v_{crit}$) reflects differences in flood plain connectivity among sites. For instance, the consistent increase in acceptable habitat ($v < v_{crit}$) area in sites 2 and 3 over the duration of the entire hydrograph (Fig~~ure~~. 7 e–f) is likely a result of their large available floodplain area (Fig. 2). Conversely, Site 1 experienced a wider range of increases in acceptable area after LW addition with the smallest differences occurring around the peak discharge (Fig. 7 d). This is likely the result of water completely inundating the site's relatively smaller available floodplain area (Fig~~ure~~. 2) during the rising limb of the hydrograph.

Similar to the modelling results for velocity the proportion of the wetted channel with acceptable habitat for fish to shelter within channel bed sediment increased for all flow levels during the entire hydrograph simulations in all study sites (Fig~~ure~~. 7 a–c). The percentage of the channel bed with stable substrate ($\tau < \tau_c$) before LW varied between 30% and 92% in Site 1, between 28% and 70% in Site 2 and between 41% and 79% in Site 3. These ranges increase on average 27-30% to 68–93 % in Site 1, 57–82% in Site 2 and 76–94 % in Site 3 (Fig~~ure~~. 7 a–c). Unlike what was observed for velocity, there were significant temporal variations in the proportion of the wetted channel with stable substrate ($\tau < \tau_c$), especially at Site 1 (Fig~~ure~~. 7d) which experienced the widest range of change between -2% and 42% (Table 3). In this ~~site~~site, the greatest increase in relative habitat area occurred at the peak of the hydrograph when presumably conditions would be the harshest for juvenile Coho Salmon (Fig~~ure~~. 7 d). In other words, the greatest increases of proportional area with stable substrate after LW addition coincided with the high discharge, while smaller differences took place at the initial low discharge values. In addition, larger immobile substrate areas were evident during the falling limb of the hydrograph compared to the rising limbs in all sites (Fig~~ure~~. 7 d–f). This is likely associated with temporary storage of water in the floodplain after the addition of LW and a related decreased transport capacity (decreased shear stress) available to mobilize bed material.

Table 4. Hydrograph modelling results for habitat metrics of velocity ($v \leq v_{crit}$[a]) and shear stress ($\tau < \tau_c$[b]) expressed as the range of the percentage of the channel bed pre- and post-LW; and change in percentage ~~change in~~ available as fish habitat pre- and post-LW~~.~~

	Site 1		Site 2		Site 3	
% of Bed	Pre-LW	Post-LW	Pre-LW	Post-LW	Pre-LW	Post-LW
$v \leq v_{crit}$[a]	15–36	31–74	27–74	48–85	23–38	42–72
~~%~~ change in %	16–42 (29)		12–27 (23)		24–35 (29)	
$\tau < \tau_c$[b]	30–92	68–93	28–70	57–82	41–79	76–94
~~% c~~change in %	-2–42 (28)		13–32 (27)		16–36 (30)	

[a] v_{crit} is 0.5 m/s

[b] τ_c is the critical shear stress for the movement of the median grain size (Table 1)

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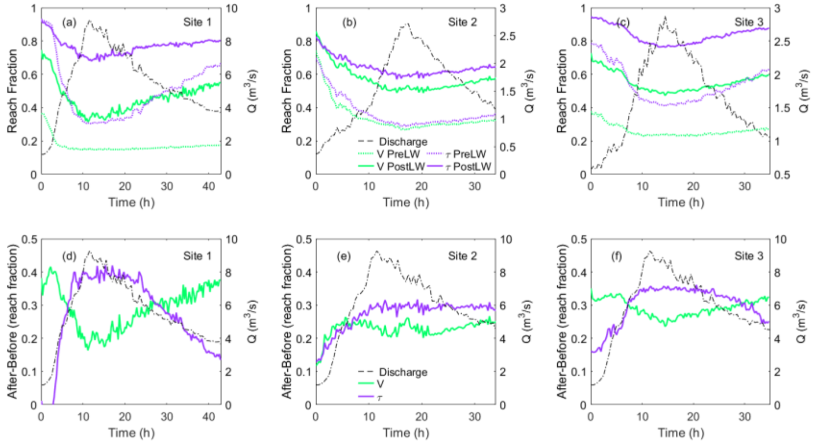

Figure 7: a–c: Fraction of the flow domain with $v < v_{crit}$ or $\tau < \tau_c$ during simulated 40–35 hour bankfull flow events in the 3 study sites pre- and post LW; d–f: differences between after and before LW~~D~~ additions in the fraction of the ~~flow~~reach area with $v < v_{crit}$ or $\tau < \tau_c$.

4 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 simulated winter rearing habitat in all sites. To our knowledge, this study is the 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 in 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 velocity~~v~~ calibration data in pre- and post-LW models provided a robust framework to estimate mean depth-averaged flow velocity and ~~v and~~ shear stress~~τ~~, variables likely to fully represent realistic winter sheltering opportunities for juvenile fish in terms of flow velocity~~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 velocity ~~v~~ and shear stress ~~τ~~ with overall lower mean values. The shapes of pre-LW velocity~~v~~

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distributions for all sites were similar to those observed in small mountain streams with large frequency at both intermediate and low velocity ~~v~~ values (Cienciala and Hassan, 2016). The shape of the velocity ~~v~~ distributions changed dramatically post-LW being characterized by a higher proportion of low velocity ~~v~~ areas in all three sites. Other field modelling efforts have documented similar effects of LW on the velocity ~~v~~ distribution in the flow field (Wall et al., 2016). Flume experiments as well as field simulations have also reported reductions in flow velocity~~v~~ with increasing large wood obstacles (He et al., 2009; Davidson and Eaton, 2013; Hafs et al., 2014). The distributions of shear stress ~~τ~~ also changed dramatically from closely resembling those observed in single thread streams pre-LW (Lisle et al., 2000; Mueller and Pitlick, 2014; Segura and Pitlick, 2015a; 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 shear stress~~τ~~ is likely attributed to shear stress~~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 velocity ~~v~~ and shear stress ~~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 studies (Swales and Levings, 1989; Bell et al., 2001), no quantification of the actual changes in the flow field in terms of velocity ~~v~~ or shear stress~~τ~~ had been conducted before. The post-LW distributions of shear stress~~τ~~ and velocity~~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 velocity ~~v~~ refuges in close proximity to feeding locations and cover from predators (Nickelson et al., 1992a; Nickelson and Lawson, 1998; Gustafsson et al., 2012). The increase availability of low velocity ~~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 velocity ~~v~~ and shear stress ~~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 velocity ~~v~~ and ~~τ,~~ shear stress, 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 areas of elevated ~~τ~~shear stress, 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 with important impacts on the assessment of available habitat (Mutz et al., 2007)~~.~~. While it has been observed that 3D models outperform 2D models in predicting flow structures in close proximity to obstacles (Shen and Diplas, 2008), our results are promising. The full depth penetrating size and downstream orientation of the LW pieces in our reaches resulted in predictions of fragmented flow, increased maximum local shear values, deflection of maximum velocities and shear stress away from the outside of bends, and low velocity habitat regions in the wake of longitudinally oriented logs which align with observations made in other studies using 3D modelling (Daniels and Rhoads, 2003, 2004b, a; Xu and Liu, 2017). Despite these promising observations, there still remains uncertainty

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around the 3D nature of the flow, which is likely greater in areas with denser LW loading and greater stream curvature and during periods of increased discharge (Daniels and Rhoads, 2004a). A comparison of observed and modelled velocity values near LW structures would provide further understanding of the uncertainty of our 2D modelling approach and insight into the accuracy of the predictions. A comprehensive set of measurements could show a potential envelope around complex LW structures where model predictions are less accurate. However, this was not possible in our case given logistical constrains to collect such data. 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 velocity and~~v~~ ~~and~~shear stress ~~τ v~~ values, particularly where we predicted the highest values. Another limitation of our approach is the inability to account for LW 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 (Daniels and Rhoads, 2004a), 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. As the LW jams continue to develop over many flow events, in addition to some movement of logs, smaller wood pieces, sticks, and leaves from the upper watersheds will also collect and have been shown to meaningfully alter flow through LW jam (Manners et al., 2007).

Despite these uncertainties, the strong agreement between observed and predicted water surface elevation and velocity ~~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 in the regions where LW blocks flow is available to allow for conveyance through the model domain in such small streams.

The reach scale of this study should also be considered in viewing the results. Fully loading the watershed with LW at a similar density to our study sites may reduce the increase in WSE slope we observed after the addition of LW by backwatering areas where our downstream boundary conditions were located. This may lead to less heterogeneity of velocity and shear stress in the flow field, particularly fewer values in the medium to high range. However, the ~~The~~ changes in the flow field we 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 velocity~~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 the availability of such habitats, especially during high flows, may be a critical factor in increasing overwinter survival. The spatial arrangement of these low velocity~~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~~–~~ velocity~~v~~, depth, and cover into the habitat-modelling process would be a 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 velocity ~~v~~ and ~~□~~shear □□□□□□ (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; Wohl and Jaeger, 2009; Merten et al., 2010; Ruiz-Villanueva et al., 2016) given not only difference in size (e.g., smaller sites being more narrow) but also differences in discharge. 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 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 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 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 distribution of shear stress in a study of this kind.

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

Data availability. Nays2D predicted distributions of velocity and shear stress are ~~currently being process at~~available at the ScholarsArchive@OSU ~~and will be publically available soon. If the files are required sooner for the review please contact Catalina Segura~~ (https://ir.library.oregonstate.edu/concern/datasets/br86b895f)~~(segurac@oregonstate.edu).~~

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Acknowledgements

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