Spring 2019

Preliminary Impacts of Constructed Log Jams on Streambed Topography and Bed Temperature on the South Fork Nooksack River

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Abstract:

Salmon are an essential part of the culture, ecology and economy of the Pacific Northwest region of North America, but populations of some ecotypes are declining. One specific population, the Puget Sound chinook (*Oncorhynchus tshawytscha*), is listed as threatened under terms of the U.S. Endangered Species Act (ESA). The decline of this ecotype has implications not only for humans but also for all links of the ecosystem such as the populations of southern resident killer whales (*Orcinus orca*) which prey predominately on chinook salmon. Major threats to these fish include overharvest and habitat degradation due to anthropogenic factors. In an effort to help the recovery of these fish, and all salmon species, many habitat restoration projects have focused on the construction of engineered log jam (ELJ) structures. This investigation seeks to evaluate the effectiveness of such structures to create deep pools and provide pockets of thermal and velocity refuge for salmon in thermally impaired waters. Spline interpolation and overlay of temperature data was conducted using ArcGIS Pro for bed topography and temperature data collected at plots on the South Fork of the Nooksack River. A before-after control-impact study design was used. Preliminary results show equivocal differences in bed topography before and after ELJ construction (2/4 plots got significantly deeper). Temperature showed no significant effect with respect to treatment. Finally, a Python script was written to efficiently recreate this analysis in future years once more data have been collected.

Introduction:

Background

The culture, ecology and economy of Pacific Northwest region of North America is intrinsically linked with the presence and abundance of Pacific salmon (*Oncorhyncus spp.*) (Helfield et al. 2006, Turner and Berkes 2006, Duffield et al. 2007, Turner and Clifton 2009). Salmon have acted as an essential resource for the indigenous peoples of North America for generations (Turner and Berkes 2006, Turner and Clifton 2009). The profound significance of these fish is deeply ingrained within the culture of the indigenous coast people of the Pacific Northwest, frequently making appearances in their art, mythology and oral tradition (Turner and Berkes 2006, Turner and Clifton 2009). In addition to their cultural importance, salmon serve numerous ecological functions. The surge of nutrient rich organic matter associated with the return of salmon to freshwater during their annual spawning migrations acts as food source for many species and therefore an important vector for the introduction of large quantities of marine-derived nutrients into river and riparian systems (Helfield and Naiman 2006). Finally, wild Pacific salmon provide the basis for a multi-billion dollar global commercial fishing industry that feeds millions of people worldwide (Duffield et al. 2007).

Of special importance to this investigation is *Oncorhyncus tshawytscha*, also known as chinook, king, tyee or blackmouth salmon. Chinook salmon are the largest of all Pacific salmon species and as such, have significant cultural and ecological value (USEPA 2018). In the Salish Sea specifically, chinook salmon act as the dominant food source for two populations of resident killer whales—the southern resident killer whale (SRKW) and northern resident killer whale (NRKW)—both of which are listed as being of conservation concern (Velez-Espino et al. 2014). The population of chinook salmon native to the Puget Sound watershed have been listed, along with seven other evolutionarily significant units, as threatened according to the U.S. Endangered Species Act (NMFS 1999). This listing is, in part, due to the approximately 60% decline in overall chinook population since monitoring began by the Pacific Salmon Commission in 1984 (PSC 2011). Major threats which have been identified as contributing factors to this decline include overharvesting and habitat degradation in the form of thermal impairment which is caused by anthropogenic factors such as deforestation, water diversion and urbanization, and lack of deep complex pools (Richter and Kolmes 2005). Specifically susceptible to these threats is the early (i.e., spring and summer run) population of Puget Sound chinook, as these fish spend the duration of the summer waiting in freshwater before spawning in fall and therefore need sources of cool water refuge.

Large woody debris (LWD), log jams and their associated wood-formed pools provide numerous functions to the aquatic ecosystem including but not limited to flow impediment, flow deflection, bank and bed armoring, a source of substrate for macroinvertebrates, channel aggradation, cover for fish and temperature refuge (Bilby and Bisson 1998). Specifically relevant to this investigation is the process though which log jams deflect fast flowing water around and down, resulting in the formation of deep scour pools. Functions of LWD-formed pools which specifically support the successful over-summering and spawning of early-run chinook salmon include cover, velocity refuge and thermal refuge, as these fish spend long periods of time waiting in fresh water before spawning. In addition to providing cover and refuge from the faster flows of the main channel, deep pools tend to maintain more stable and cooler summer temperatures relative to other habitat features (Ward 1985). Their ability to provide energetically and thermally favorable habitat makes LWD-formed pools a highly beneficial habitat feature (Nielsen et al. 1994).

Due to the importance of LWD-formed pools and historic losses due to intentional clearing and harvest of riparian vegetation, construction of engineered log jam (ELJ) structures has become a common technique used in salmon habitat restoration efforts. Although billions of dollars of government money have been spent on salmon habitat restoration projects, there is a relative lack of funding and effort allocated to subsequent monitoring (Bash and Ryan 2002). Therefore, numerous projects may be relying on techniques whose effectiveness have not been adequately evaluated (Palmer 2009). This investigation seeks to quantify the effectiveness with which ELJ structures can enhance salmon habitat in thermally impaired waters, with respect to streambed topography and relative bed temperature at the Nesset's Reach section of the South Fork of the Nooksack River.

Study Site

The study site is Nesset's Reach, a 2.6 kilometer stretch of the South Fork of the Nooksack River located near Acme Washington which has been identified as a priority for restoration (WRIA 1 Salmon Recovery Board 2005) (Fig. 1) In this reach, elevated stream temperatures and lack of large deep pools have been identified as two major stressors that negatively affect early run chinook (WRIA 1 Salmon Recovery Board 2005, Soicher et al. 2006). In 2013 the Nooksack Tribe's Natural Resources Department, with funding from Washington State's Salmon Recovery Funding Board, began the initial stages of planning and implementing a habitat restoration program using engineered log jam (ELJ) structures at Nesset's Reach (NNR 2015). This investigation uses data collected in and around those ELJ structures by James Helfield and associated students from Western Washington University during the summers of 2015-2018.

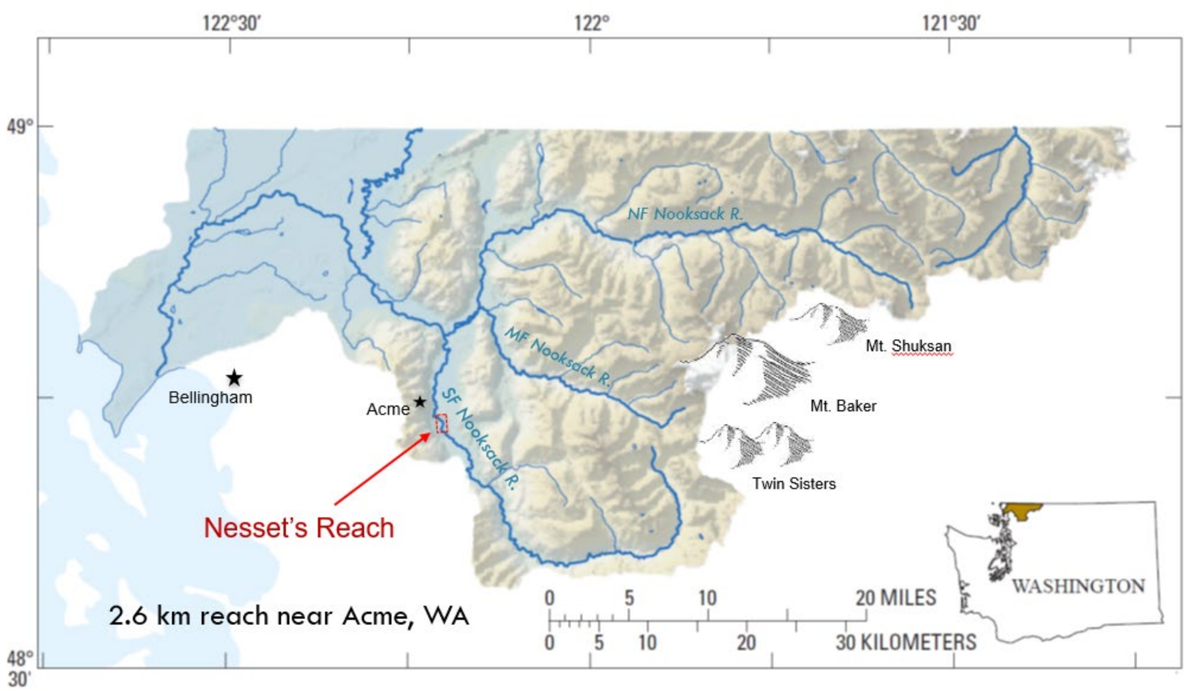

Figure 1 | Overview of Nesset's Reach study site location in relation to familiar landmarks.

Methods:

Sampling Design

The sampling design follows a before-after control-impact (BACI) design, where before-after describes when the plot was sampled with respect to the timing of the ELJ construction and control-impact describes whether an ELJ was built. For pre-construction (i.e., “before”) plots, a 225m^2 grid (15m x 15m) centered around the presumed centroid of the resulting ELJ formed pool was sampled at 2.5m intervals. Post-ELJ data collection was repeated in and around the resulting pool. Bed elevation (cm) was measured at each point along the grid using a surveyor’s level (LT6-900N Level-Transit, David White Instruments, Watseka, IL) or an electronic total station apparatus (CST202, CST/Berger, Wateska, IL), following procedures described by Bain and Stevenson (1999). Water temperatures (°C) were measured on the stream bed using an instant-read thermometer (Digi-Sense 400 Series Thermistor Thermometer, Eutech Instruments, Singapore) at 5m intervals, however there was some variation in spatial distribution of samples due to difficulties navigating complex pools.

Data Analysis

Preliminary data processing was conducted to convert bed topography and temperature measurements into relative values that could be compared between plots. Measured bed topography values (cm) were first adjusted by subtracting them from an arbitrary constant of 1,000 resulting in a value for relative bed elevation (RBE). RBE (cm) was then converted to a surrogate for Residual Pool Depth (i.e., maximum pool depth minus tail-out depth), referred to in this investigation as Pseudo Residual Pool Depth (PRPD). PRPD was calculated by subtracting the plot’s maximum RBE value from all other RBE values, with the lowest PRPD values indicating the lowest bed elevations and deepest point within each plot. Minimum PRPD (i.e., maximum depth) values were calculated for each plot in each year, and mean PRPD values were obtained from PRPD values for each sampling point within each plot in each year. Raw bed temperature (°C) was then transformed into relative temperature by subtracting each measured temperature from simultaneously recorded temperatures at the U.S. Geological survey gauge approximately 2 km upstream (USGS 12210000).

This investigation used ArcGIS Pro (Version 2.2.4, Environmental Systems Research Institute, Redlands, CA) as its dominant spatial analysis software. Spline interpolations of PRPD were constructed for each plot to convert discrete bed topography measurements into a continuous two-dimensional raster surface. This process was subsequently automated using Python (Version 3.6.5, Python Software Foundation, Beaverton, OR) and the Arcpy module. Relative bed temperatures were then associated with bed topography sample points using a tabular join. The resulting point feature class was symbolized according to relative bed temperature (red for warmer and green for cooler with variable sizing to indicate the magnitude of difference) and then overlaid on top of PRPD splines for visual interpretation. Six case study plots were selected for statistical analysis using R-Studio (Version 3.6.0 "Planting of a Tree", The R Foundation for Statistical Computing, Vienna, Austria), three of which had four years of pre-ELJ data and three of which had data for before and after log jam construction. For the pre-ELJ plots, one-way analysis of variance (ANOVA) were conducted, comparing mean PRPD between plots over the four years data has been collected (2015-2018). Before/after plots were compared using a two-sample, two-factor paired t-test.

Results:

Case Study Pre-Jam Plots

Plot level trends in maximum PRPD for pre-ELJ case study plots show notable variation between years (Fig. 2). Results of one-way ANOVA comparing mean PRPD between years indicate significant differences for all plots (N2124: $F_{(3,183)} = 49.76$, p-value <<0.05; N2344: $F_{(3,187)} = 50.57$, p-value <<0.05; N3439: $F_{(3,185)} = 7.985$, p-value <<0.05). Pairwise relationships between years determined using a Tukey HSD test are displayed below using lowercase letters (Fig. 2). Spline interpolations of each plot in 2015 and 2018 with overlaid temperature data suggest no significant differences in PRPD or temperature over the study period (Fig.3).

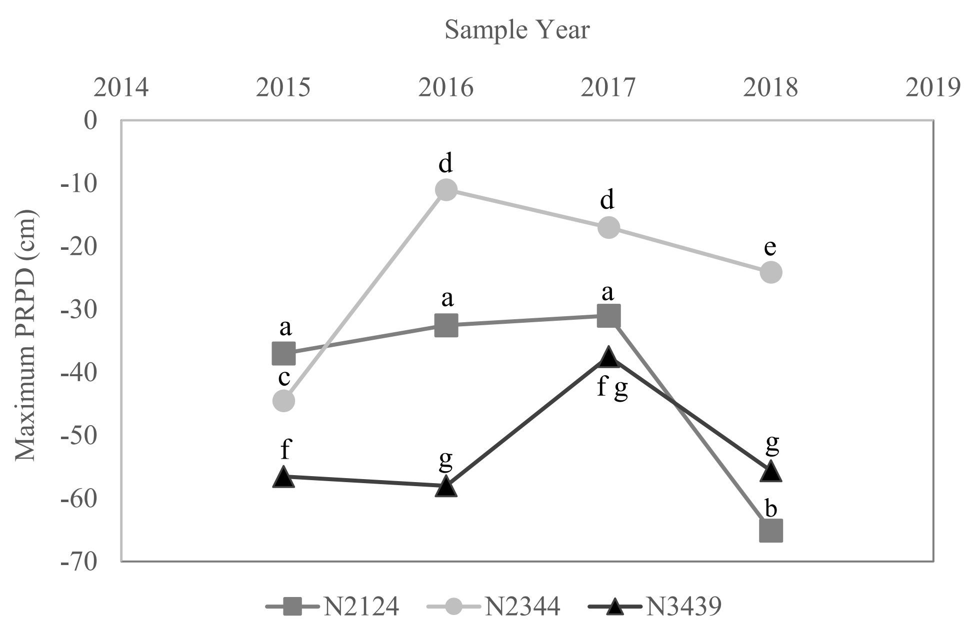

Figure 2 | Plot level PRPD (cm) trends for three pre-jam case study plots. Superscript letters describe significant differences between mean PRPD over the sample period (Tukey HSD, $p < 0.05$).

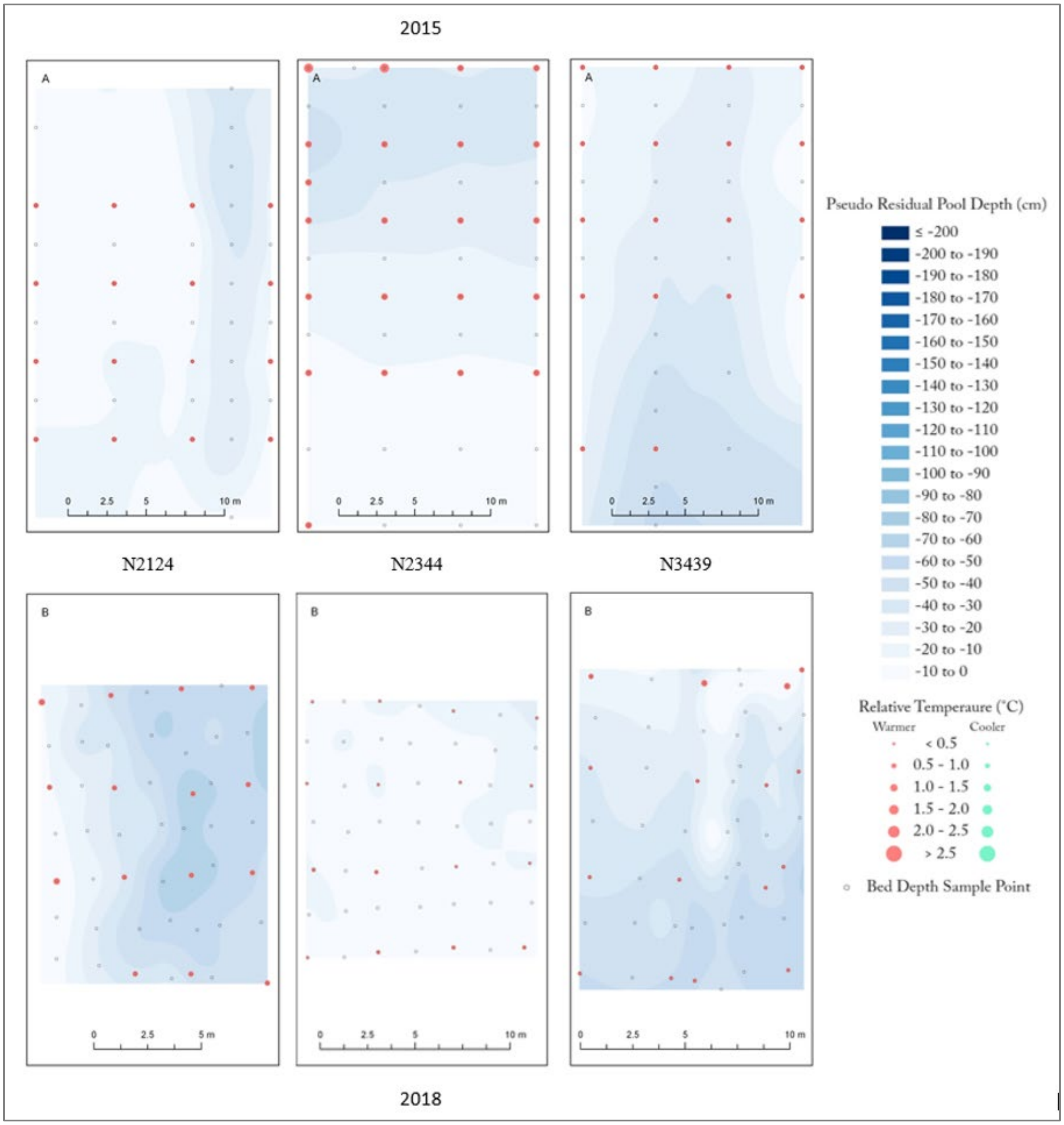

Figure 3 | Spline interpolation with overlaid sample points and relative temperature for no-ELJ plots in 2015 and 2018. Plots are paired vertically in A-B pairs.

Case Study Impact Plots

Plot level maximum and mean PRPD trends for impact case study plots show statistically significant pool creation for plots N1301 and N1304, but there was no significant difference between pre and post-ELJ PRPD for plot N1313 as indicated by two-factor, two-sample, paired t-tests (N1301:$T_{(2)\,40} = 18.3$, p-value <<0.05; N1304: $T_{(2)\,30} = 7.36$, p-value << 0.05; N1313: $T_{(2)\,41} = 1.47$, p-value = 0.148) (Figs. 4 & 5). The spline interpolations of PRPD for the case study impact plots corroborate these findings visually (Fig. 6).

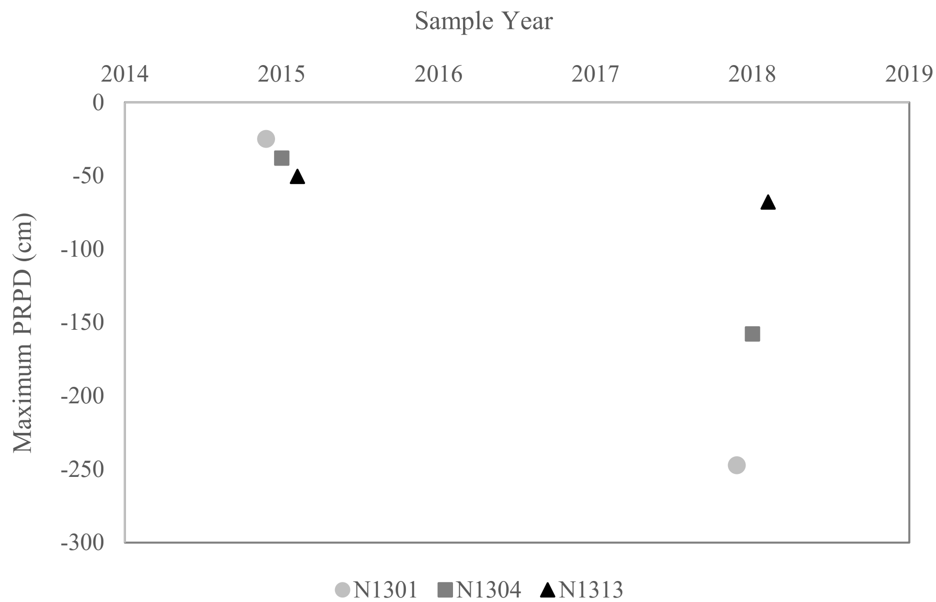

Figure 4 | Plot level maximum PRPD (cm) trends for three impact case study plots. Values for 2015 and 2018 represent before and after the construction of an ELJ structure.

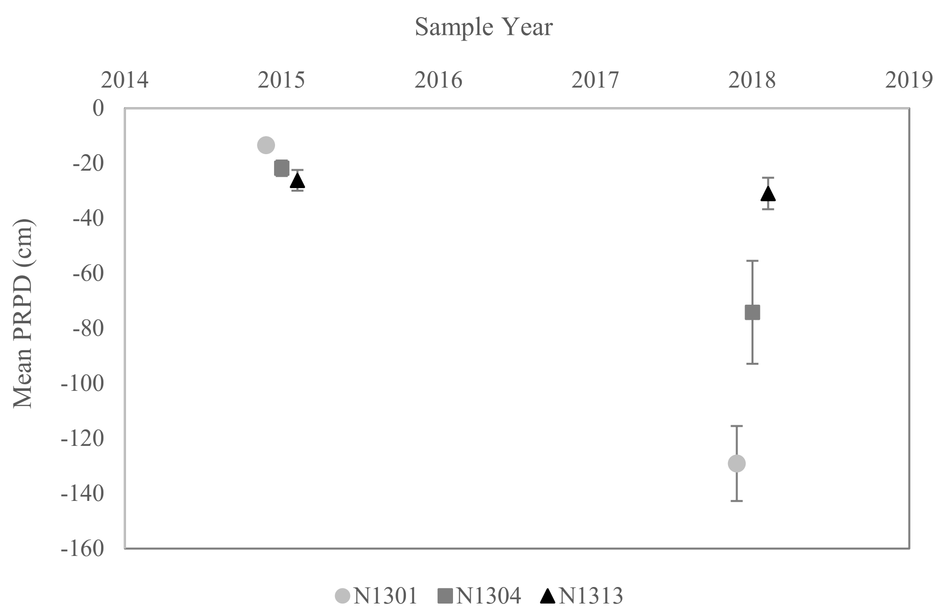

Figure 5 | Mean PRPD (cm) of the three case study impact plots both before and after ELJ construction in 2015 and 2018 respectively. Error bars represent 95% confidence intervals.

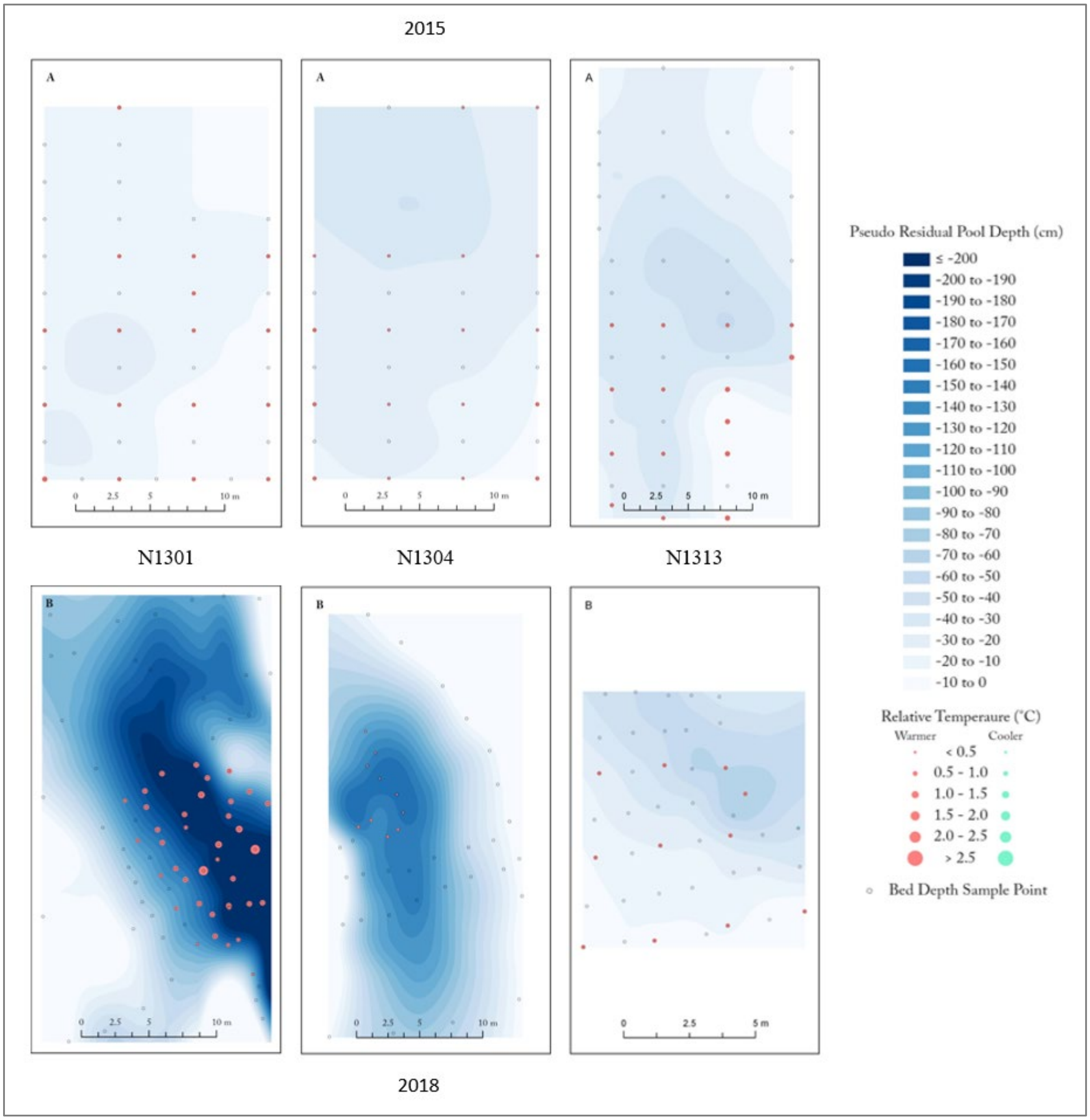

Figure 6 | Spline interpolation with overlaid sample points and relative temperature for ELJ impact plots in 2015 and 2018. Plots are paired vertically in A-B pairs.

Study Level Results

Study level maximum PRPD trends comparing both control and impact plots before and after ELJ construction indicate limited differences in response to ELJ structures (Fig. 7). Only two of the four impact plots show a noticeable decrease in maximum PRPD (Fig. 7). Maximum PRPD values in all other plots range from approximately 0-70 cm deep (Fig. 7).

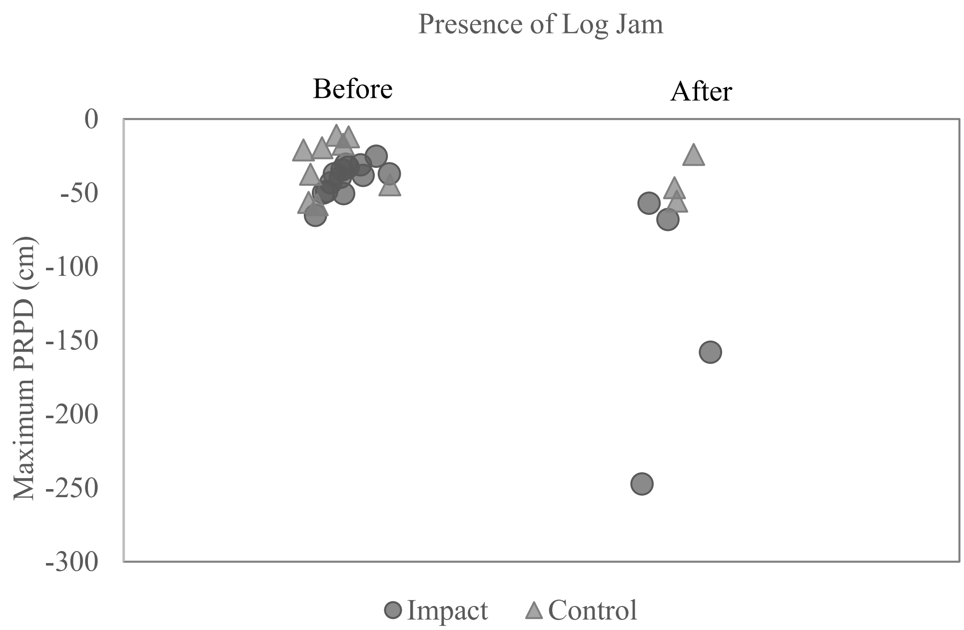

Figure 7 | Study level maximum PRPD (cm) trends before and after log jam implementation for both control and impact plots.

Study level mean relative temperature trends display limited noticeable differences between control and impact plots before and after ELJ construction (Fig. 8).Post-ELJ relative temperatures stayed within the range of values observed in pre-ELJ plots, and the only two plots that demonstrated negative mean relative temperatures were in the pre-ELJ group, indicating no significant decrease in overall pool temperature with respect to treatment (Fig. 8).

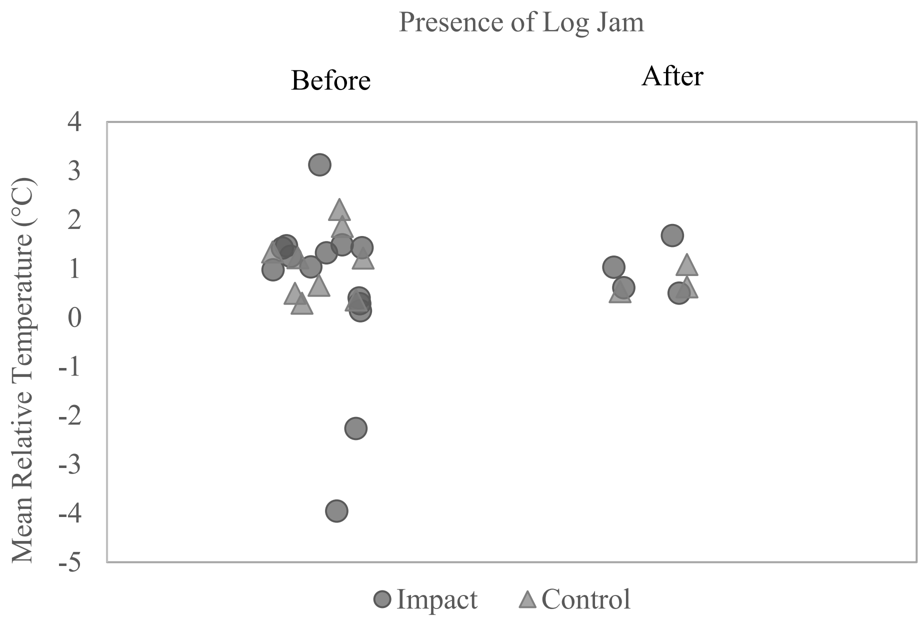

Figure 8 | Study level mean relative temperature (°C) trends before and after log jam implementation for both control and impact plots.

Discussion:

The case study plots used in this analysis outlined preliminary trends for PRPD and relative bed temperature. The annual variation in PRPD of pre-jam plots visible in Figure 2 illustrates the dynamic nature of streambed topography in response to natural environmental conditions. This variation, along with limitations in data quantity, influenced the ability of this analysis to conduct meaningful statistical comparisons between years. Although one-way ANOVA and Tukey HSD results are reported above, such calculations have low power and therefore should be considered as such. Additionally, in the context of this investigation statistical significance and ecological significance are not necessarily the same. The significant variation in PRPD between years that is evident in Figure 2 is not ecologically significant, as none of the pools reached a depth greater than 1m. The ELJ structures used in this investigation are intended to create pools that are greater than 1m deep, which is the threshold for what constitutes a deep pool from the perspective of salmon habitat (NNR 2015). Therefore, visual interpretation of spline interpolations with overlaid temperature data will be a sufficient means of quantifying significance in this preliminary analysis, and more pronounced statistical trends may become apparent as more post-ELJ data is incorporated from subsequent years.

Spline interpolations of PRPD data from impact plots depict an increase in pool depth for two out of the four plots for which we have data. Although this result is somewhat equivocal, similar investigations with broader datasets suggest that the formation of deep scour pools as a result of ELJ structures can take up to 4-5 years to take full effect (Walls et al. 2019). The one year of post-ELJ data that is incorporated into this analysis is likely insufficient to fully quantify the impacts of ELJ structures on bed topography. Specific reasons that two of the four impact plots show no significant change after ELJ construction could be attributed to the fact that some of the ELJ structures were constructed more peripherally with respect to the low-flow channel, and therefore were not as fully engaged by the river flow. Those structures may therefore have experienced insufficient height of peak flows to cause noticeable scour and/or possible channel migration during the study period resulting in the separation of the ELJ structure from flow.

Study level temperature trends reported in this analysis suggest no significant relationship between ELJ-formed pools and cooler water temperatures. This may be in part due to the limited quantity of data and therefore may be partially explained through the findings of Walls et al. (2019). The observation that all of the plots have temperatures greater than the USGS reference station is somewhat perplexing and not fully understood. One possible explanation is that the temperature gauge at the USGS reference station is in a relatively deep pool that is well shaded and approximately 2 miles upstream of the sample site. These factors may contribute to the comparatively cooler temperature of this reference cite resulting in artificially high relative temperatures, but they would not explain why relative temperatures did not decrease in plots where deep pools developed.

Conclusions, Limitations and Next Steps:

Overall conclusions of this study suggest that ELJ structures may indeed result in the formation of scour pools, but our results were somewhat equivocal. Additionally, this study found no significant relationship between ELJ formed pools and reduced stream temperatures. The major limitation of this study came back to insufficient data quantity. Only one year of post-jam data had been collected at the time of this analysis, providing low statistical power and limited ability to draw meaningful conclusions.

In the coming years as additional data are collected for this project, this analysis may be repeated quickly and efficiently through the use of Python. As a final step in this analysis we created a Python script using the Arcpy module which automates spline production. This script consists of a function defined as NessetSplineMachine(). This function prompts the user to input the file paths and names a properly formatted Excel file containing the data and the location of an ESRI geodatabase for output files. The script will then automatically conduct the analysis and store outputs in the selected geodatabase. Therefore, although the results of this analysis may have been ambiguous and limited, future iterations of this process may benefit from the procedure that was set forth and the Python script that was created.

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