Impacts of the Elwha River Dam Removals on Chinook Salmon (*Oncorhynchus tshawytscha*) Spawning Habitat

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A thesis

submitted in partial fulfillment of the

requirements for the degree of

Master of Marine Affairs

University of Washington

2021

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Abstract

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Streambed particle size is a key factor influencing Chinook salmon (*Oncorhynchus tshawytscha*) spawning site suitability. Both the construction and removal of dams alter the sediment in rivers, resulting in changes to suitable habitat for salmon. When in place, dams impede the movement of sediment, resulting in an accumulation of sediment above the dam and a degradation of the riverbed below the dam. The release of this accumulated sediment after dam removal can restore a more natural distribution of sediment size classes below the dam, potentially improving salmon spawning habitat. Dam removal for the purpose of river restoration and improving conditions for salmon has increased in recent decades. The purpose of this study is to assess the effects of the sediment released from two large dam removals on the Elwha River in Washington state on streambed particle size, and the resultant amount of suitable spawnable habitat for Chinook salmon. Pebble counts were conducted in 45 riffles in 2009, before dam removal, and in 21 riffles in 2015, after dam removal, in the mainstem of the Lower and Middle sections of the Elwha River. The fraction of movable particles by a spawning Chinook salmon in the riffle crests increased by 43% after dam removal, resulting in more suitable spawning habitat.

After dam removal, there was greater variation in sediment size within riffle crests, whereas there were predominantly larger particles before dam removal. The positive changes in sediment measured in this project support the concept that dam removal is a meaningful strategy for salmon restoration.

Introduction

Dams harm river ecosystems and their productivity (Barbarossa et al. 2020, Bellmore et al. 2019, Poff and Hart 2002). River systems are by nature highly dynamic and variable, and their health and integrity are dependent on their changing conditions (Poff 1997). Dams change flow regimes, water quality, water chemistry, water temperature, river morphology, and the natural movement of sediment and woody debris through river ecosystems (Barbarossa et al. 2020, Magilligan et al. 2016, Poff and Hart 2002). Dams can be barriers that cause fragmentation and disrupt river connectivity, which impedes or prevents the up- and downstream migration of both organisms and nutrients (Barbarossa et al. 2020, Bellmore et al. 2019, Pess et al. 2008, Poff and Hart 2002). The combined effects of these changes make dams one of the leading causes of freshwater biodiversity loss (Magilligan et al. 2016, Cooper et al. 2017).

Anadromous salmonid species depend on freshwater river ecosystems for access to both spawning and rearing habitat, and are particularly vulnerable to the negative impacts of dams (Pess et al. 2008). Along with habitat degradation, fishing, and climate change, dams are one of the primary causes of declines in salmon populations (Nehlsen and Lichatowich, 1991). Many salmon populations based in dammed rivers are listed as either threatened or endangered under the United States Endangered Species Act (Myers, 1998). Specifically, the loss of available spawning habitat due to blockages from dams is a key factor influencing salmonid population declines (Harrison et al. 2019). While dam removals in the United States are occurring for a number of different reasons, including the removal of aging, unsafe, and obsolete structures, their removals are increasingly being used as tools for ecosystem management and restoration (Peters et al. 2017, Foley et al. 2017). In recent decades the number of large dam removals has increased for the purpose of river restoration in the Pacific Northwest (Blumm and Erickson, 2012). Understanding the abiotic and biotic ecosystem changes in rivers after dam removals, and how they impact salmonid populations, is essential to these recovery efforts (Bellmore et al. 2019).

In 2011, final approval was given to remove the Elwha and Glines Canyon dams on the Elwha River on the Olympic Peninsula in Washington State. The two dam removals there were the largest in history, by both height and trapped sediment volume (Ritchie et al. 2018). Built in the early 1900s, the Elwha and Glines Canyon dams had no fish passage and resulted in lasting impacts on the morphology of the river, the ecology and populations of species in the river, and the surrounding communities (Duda et al. 2008). The Elwha dam was the first to be built; it cut off an estimated 90-95% of the watershed and disconnected the upper and lower sections of the river from any fish migration, followed by the Glines Canyon dam further upriver (Brenkman et al. 2019, Pess et al. 2008). During the century when the dams were in place, the Elwha River salmonid populations are estimated to have declined by 90% (Pess et al. 2008). The dam removals began in 2011, and the Elwha dam was passable by salmon by 2012 (Brenkman et al. 2019). Removal of the Glines Canyon dam was completed in 2014, while fish passage was finalized in 2015 (Brenkman et al. 2019). One of the express purposes for the removals of the Elwha River dams was for ecosystem restoration with a particular focus on the recovery of the river's struggling salmon populations (Peters et al. 2017).

While the dams caused several changes to the river ecosystem, they played a particularly large role in altering the natural movement of sediment. The two dams withheld approximately 30 million megatons (Mt) of sediment from the lower 20 kilometers of the Elwha River. The lack of this sediment changed the composition of the riverbed in the sections of the Elwha River between and below the dams over the course of decades (Ritchie et al. 2018).

Anticipating the sediment release from behind the dams posed a challenge for managers, as releasing such a large pulse of sediment can—and did—drastically impact water quality and groundwater elevations, change channel morphology, and alter habitat (Ritchie et al. 2018, Peters et al. 2017). In the short-term some of these changes, like a decrease in water quality due to turbidity, can be harmful to salmon, but long-term, the restoration of the natural movement of sediment can improve habitat. For example, as a result of being starved of sediment for a century, the substrate below the dams was primarily composed of both cobbles and coarse gravel (Konrad, 2009). However, above the dams, the streambed also contained smaller gravels and sand, which were prevented from flowing downstream (Konrad, 2009). The removal of the dams would ultimately allow the reestablishment of the natural movement of smaller gravels into the areas below the dams, which would improve the amount of suitable spawning substrate for salmon.

In order to spawn successfully, salmonids require the correct substrate size, water depth, velocity, and temperatures (Beechie et al. 2006, Harrison et al. 2017). Spawning nests themselves, called redds, also vary according to the species and size of the fish (Beechie et al. 2006). Chinook salmon *(Oncorhynchus tshawytscha*) often spawn in or near riffles, areas known for favorable habitat characteristics (Beechie et al. 2006, Harrison et al. 2019, Reibe et al. 2014). In particular, the crests of riffles are known for high hyporheic flow, an interphase where surface and groundwater mix. This flow can help move oxygenated water through a redd, and can also remove metabolic waste (Harrison et al. 2019). Fine sediment released during dam removal decreases the survival of incubating salmonid eggs by preventing the flow of oxygenated water, and is therefore not suitable or ideal for spawning (Peters et al. 2017). On the other hand, the released sediment also includes moderate sized substrate suitable for Chinook salmon redd construction. A large proportion of salmon mortality occurs as eggs incubate, so habitat characteristics, like fine sediment deposition or scour and fill of spawning sites, are of critical importance to salmon population size (Harrison et al. 2019, Devries, 1997). In the case of the Elwha, while the majority of the impounded fine sediment moved through the mainstem of the river and into the delta and offshore areas quickly, the streambed was still greatly altered (Ritchie et al. 2018). Understanding the potential positive and negative impacts of the changed sediment on the amount of suitable spawning habitat is therefore critical for population recovery management after dam removal (Peters et al. 2017).

Substrate size is therefore key for predicting suitable spawning habitat for salmonids (Reibe et al. 2014). The sediment must be small enough for the fish to move it effectively, but must be large enough to prevent scour (Harrison et al. 2019). When female salmon construct redds, they move onto their sides in the water and slap or swat their tail onto the substrate to dig the redd (Harrison et al. 2019, Reibe et al. 2014). Simultaneously, the fine sediment where she is digging is dislodged and carried downstream by the current, leaving coarser gravel and cobble sized grains behind, which promotes the movement of oxygen rich water through the redd (Harrison et al. 2019, Reibe et al. 2014). The sediment size a female salmon can move has been tied to her length, and therefore gravel size preferences differ between fish of different sizes (Beechie et al. 2008, Harrison et al. 2019, Reibe et al. 2014). Larger fish can construct redds in larger gravel in both faster moving and deeper water, whereas smaller fish require smaller sediment sizes and slower, shallower flows (Beechie et al. 2008). Due to these factors, spawning habitat quality with regards to substrate is highly sensitive to sediment loading, which can occur from events such as dam removal (Reibe et al. 2014).

The goal of this study is to determine the impacts of the Elwha River dam removals on the sediment composition of potential spawning sites of Chinook salmon (*Oncorhynchus tshawytscha*) in the Elwha River below the dam removals. To understand these changes, I compared the composition of sediments in riffle crests in the Middle and Lower sections of the Elwha River in 2009 before dam removal and in 2015, after removal. I hypothesized that sediment size in the riffle crests would decrease with dam removal and result in a potential increase in the amount of spawnable habitat available for Chinook salmon, due to the decrease in overall streambed particle size as well as the increase in the proportion of habitat that has particle size suitable for Chinook spawning. Second, I evaluated the Lower and Middle sections of the Elwha River after dam removal, to determine which section of the river had more spawnable habitat. I predicted that the Lower Elwha River, which was inundated with sediment from both dam removals, would have smaller, more suitable sediment sizes in the riffles compared to the Middle Elwha River riffles, and therefore a greater amount of spawnable habitat. Finally, we investigate the relationship between redd density and substrate size. I predict that redd densities will be higher in areas with more suitable substrate and in areas that saw the largest increases in suitable substrate

Methods

Study Site

The headwaters of the Elwha River are located within the Olympic National Park on the Olympic Peninsula in Washington state (Figure 1, Brenkman et al. 2019, Peters et al. 2017). The 72km long river is part of an 833km^2 watershed that ultimately drains into the Strait of Juan de Fuca (Peters et al. 2017). Uniquely, 83% of the watershed is within the National Park, which has protected the river to a great extent from development (Pess et al. 2008). The general climate in this region is made up of warm, dry summers and cool and wet winters (Duda et al. 2008). The hydrologic regime is both dominated by rain in the fall and snowmelt in the spring (Duda et al. 2008).

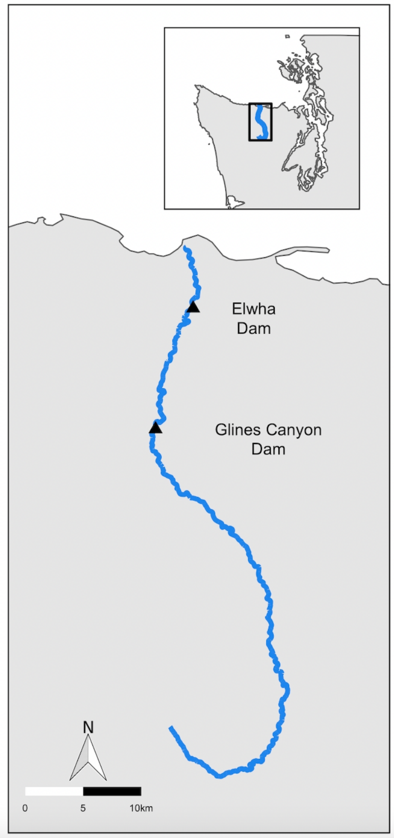

Figure 1. The Elwha River, located on the Olympic Peninsula in Washington state. The Elwha dam is at Rkm 7.9 and the Glines Canyon Dam is at Rkm 21.6.

The Elwha dam (32m in height), constructed at Rkm 7.9 and the Glines Canyon dam (64m in height), constructed at Rkm 21.6, divided the river into three sections (Foley et al. 2017). The Lower Elwha River was located below the Elwha dam, the Middle Elwha River between the Elwha and Glines Canyon dams, and the Upper Elwha River extended upstream from the Glines Canyon dam. The Elwha dam impounded the former Aldwell reservoir and the Glines Canyon dam impounded the former Mills reservoir. Dam removal, which began in September of 2011 and was completed in October of 2014, resulted in sediment from both reservoirs inundating the Lower River and the Middle Elwha River, as well as the estuary and nearshore area (Ritchie et al. 2018). The dams extirpated anadromous salmonids above both of the dams, meaning they could only access the Lower Elwha River to spawn and rear. Since dam removal salmonids have recolonized both the Middle and Upper Elwha River (Duda et al. 2021).

Pebble Count Sampling and Sediment Particle Size Distributions

In August and September of 2009 and 2015 (before and after dam removal) the flows in the Elwha River were low enough that riffle crests within the Lower and Middle sections of the river could be identified and sampled. In 2009, all 45 riffle crests located in the mainstem of the Middle and Lower Elwha were sampled. Of these, 17 were located in the Lower Elwha River and 28 in the Middle Elwha River. In 2015, 21 riffle crests were sampled, 12 of which were located in the Lower Elwha River and 9 in the Middle Elwha. Of all of the sampled riffles, twelve remained in the same location between 2009 and 2015, allowing for a comparative analysis (Figure 2, Pess et al. 2016, Peters et al. 2017).

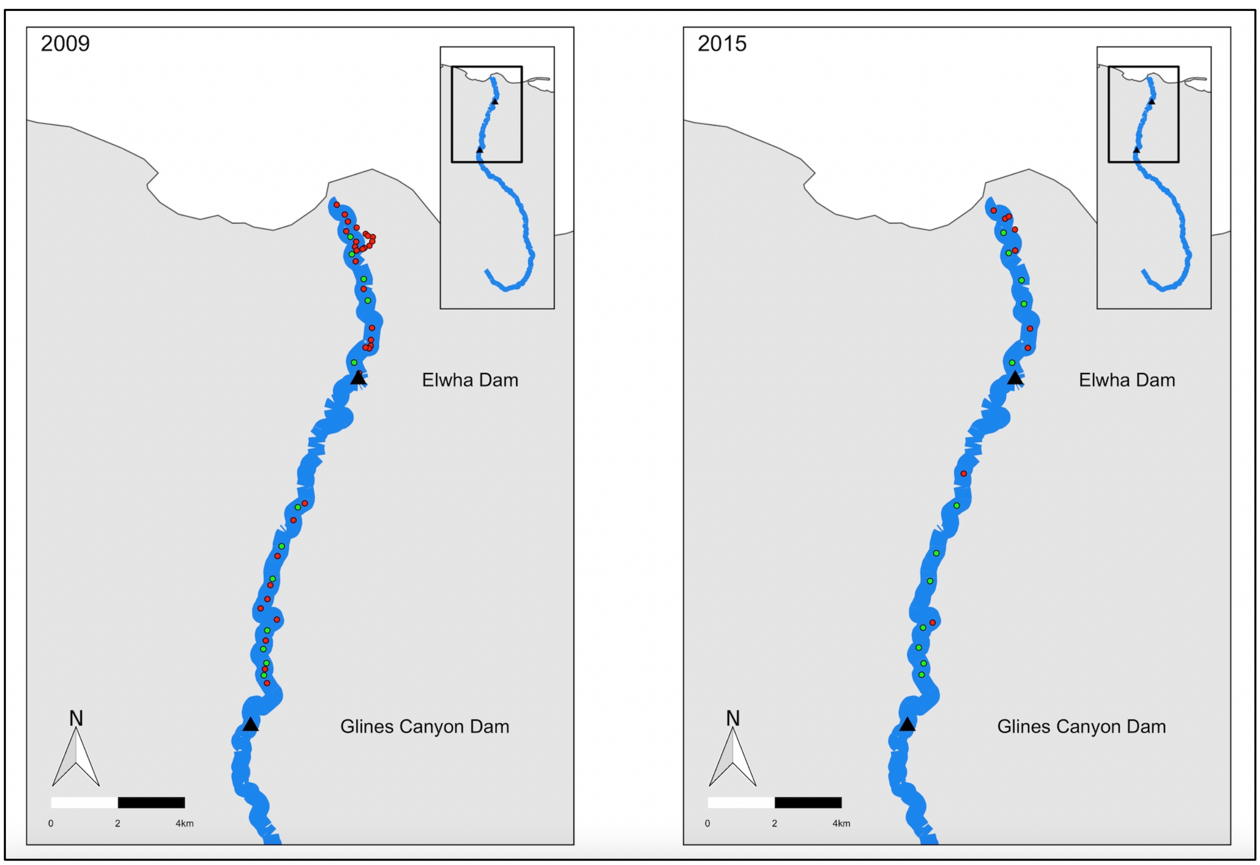

Figure 2. Sampled riffle crest locations in the Elwha River both before dam removal in 2009 and after dam removal in 2015. The twelve riffles that remained in the same location are highlighted in green as opposed to red.

In both years, identification and pebble counts were conducted and provided by members of the National Oceanic and Atmospheric Administration (NOAA) Watershed Program, both in the upstream and downstream portions of each riffle, in accordance with Bunte and Abt (2001) and Peters et al. (2017). For each portion of a riffle crest, 100 points were randomly selected within each section of the sampling areas. The particle immediately below each point was measured along the b- or intermediate-axis in accordance with Wolman (1954) and Bunte and Abt (2001). The sample particles were collected across the entire bankfull channel width at each of the riffle crest sampling sites (Pess et al. 2016).

The distribution of particle sizes in the pebble count is often characterized using quantiles and ratios of these quantiles. Common quantiles used include D_{50}, the median particle size and D_{84} and D_{16}, the particle sizes for which 84% and 16% of the sizes are smaller. If the particle size distribution is normal, then D_{84} and D_{16} are both one standard deviation from D_{50}. The ratio D_{84}/D_{16} provides a measure of variability, while D_{84}/D_{50} describes skew (Bunte and Abt 2002). Both ratios help to understand the tails of the sediment distributions. The up- and downstream portions of each riffle crest were averaged, to produce values representative of the entire riffle.

Predicting Spawning Capacity

I defined the fraction of movable particles (Fm) as described by Reibe et al. (2014). This involved two steps. First, I calculated the largest sediment grains size that would be movable by a fish of a specific length (DT) and second, I calculated the proportion of the particles (in the pebble count) that were smaller than this cut off. The diameter of the largest sediment grain size was estimated by Reibe et al. (2014) as:

$$DT = 3.3(L/600)^{2.3}$$

Here L describes fork length, which represents the size of the fish. Using fork length measurements of female Chinook salmon in the Elwha collected between 2013 and 2020, I calculated that the average female is 770mm (±39mm) in length. Thus, the largest sediment grain size that a 770mm female Chinook salmon can move is 138mm. Fm is the proportion of particles in each pebble count that is smaller than 138mm.

In order to track changes resulting from dam removal, Chinook salmon redd count data was collected in 2012-2019 throughout the entire mainstem of the Elwha River. All Chinook salmon redd count data was provided by M. McHenry, the Habitat Program Manager of the Lower Elwha Klallam Tribe. Chinook salmon redd counts conducted prior to 2012 were restricted to the Lower Elwha River due to the dams. The Chinook salmon redd density of the fifteen riffle crests that contained redds was calculated in 2015. Of these fifteen riffles, only eleven were sampled in both 2009 and 2015, and I calculated the change in Fm for these riffles.

I conducted an exploratory, graphical analysis comparing Fm and redd density in 2015 and comparing changes in Fm to redd density and Rkm. The change in Fm was used as a proxy for sediment aggradation, to compare our results to sediment aggradation that was modeled by Konrad (2009). Konrad (2009) predicts that higher aggradation would occur in specific areas of the Lower and Middle sections of the Elwha River. These areas of high aggradation would primarily be the result of smaller gravels and sand released from behind the Glines Canyon dam. I explored whether the greatest changes in Fm and density occurred in areas with the greatest predicted sediment aggradation. Quantitative analysis was not completed due to the small sample size and a lack of other habitat variables at the riffle crest level.

Statistical Analysis

I used confidence intervals to summarize statistical evidence for before and after and between river segment differences in particle size. For unpaired comparisons I used 95% confidence intervals derived from Welch's t-tests, while intervals based on paired t-tests were used for paired comparisons.

Results

Before and After Dam Removal in All Mainstem Riffles (2009 and 2015)

Sediment size in the sampled riffles decreased after dam removal, increasing the fraction of movable sediment (Fm) by 43%. In 2009, the mean fraction of movable sediment in the riffle crests was 0.57, which increased by 0.25 (CI [0.32, 0.17]) to 0.82 in 2015 (Figure 3). Median streambed particle size (D_{50}) in the mainstem riffle crests decreased by 69mm (CI [52, 85]) from 122mm to 53mm between 2009 and 2015 (Figures 4 and 5). Similarly, D_{84} also decreased by 90mm (CI [56, 125]), from 229mm to 139mm (Figures 4 and 5). The variability of the distribution of particle sizes, as measured by the D_{84}/D_{16} ratio, increased by 27.7 (CI [13.30, 41.95],) in 2015 compared to 2009 from 5.79 to 33.49 (Figure 6). Skew as measured by the D_{84}/D_{50} ratio also increased by 0.86 (CI [0.47, 1.23]) between years, from 1.95 to 2.81 (Figure 6).

Similarly, the amount of spawnable sediment increased in the twelve riffle crests in the mainstem that remained in the same location before and after dam removal. The fraction of movable streambed particles (Fm) increased by 0.32 (CI [0.21, 0.41]) from 0.47 to 0.79 (Figure 3). While Fm increased in all twelve riffle crests, the amount of change ranged from an increase of 0.16 to an increase of 0.66. The median streambed particle size in the twelve riffles decreased by 85mm (CI [60, 111]) between 2009 and 2015, from 143mm to 57mm (Figures 4 and 5). D_{84} decreased by 114mm (CI [69, 158]) in 2015, from 270mm to 156mm (Figures 4 and 5). The D_{84}/D_{16} ratio increased between 2009 and 2015, moving up by 31.35 (CI [6.87, 55.82,]) from 5.00

to 36.35 (Figure 6) and the D_{84}/D_{50} ratio increased by 1.02 (CI [0.46, 1.56]), from 1.92 to 2.94 (Figure 6).

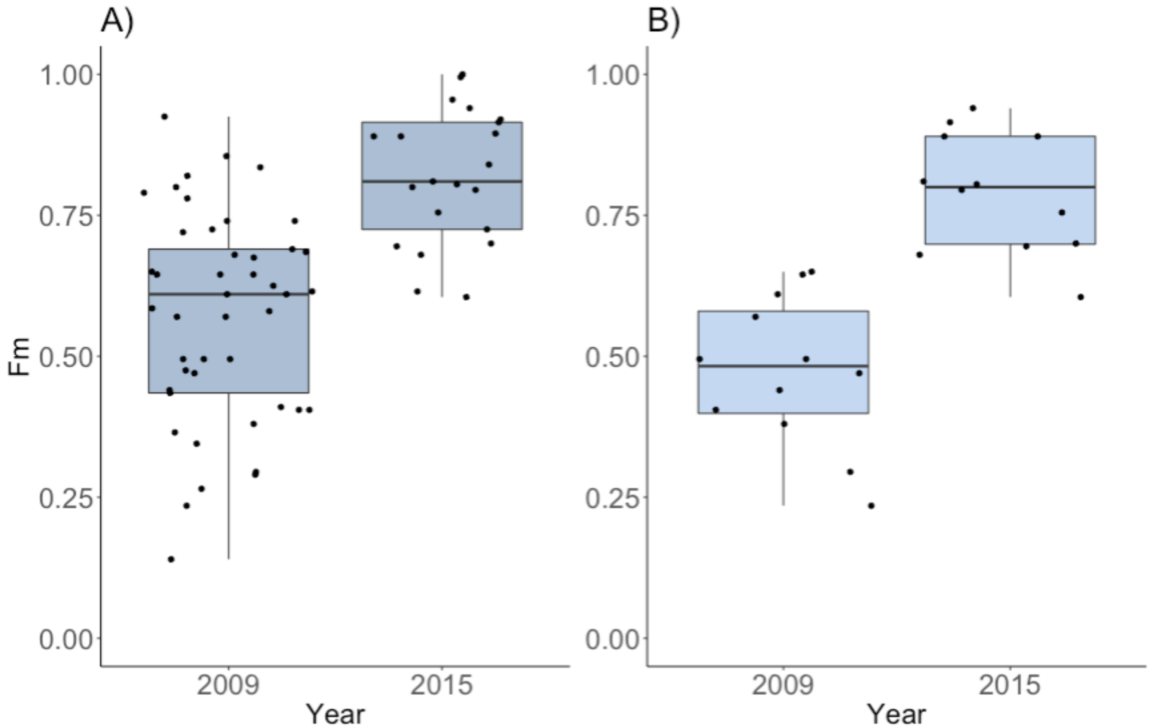

Figure 3. The distribution of the fraction of movable streambed particles (Fm) by an average length Elwha River female Chinook salmon (770mm±39mm) in all riffle crests sampled in the Elwha River between 2009 and 2015 (A), and in the 12 riffles that remained in the same location between both years (B).

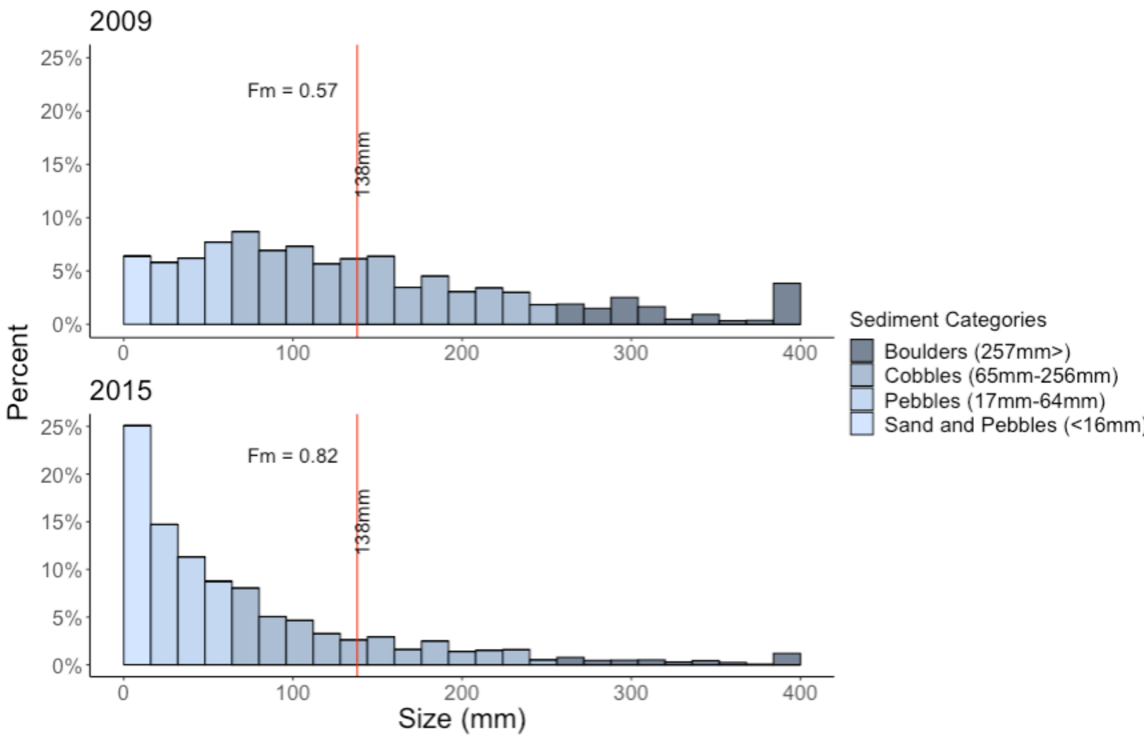

Figure 4. Pebble size distribution in all sampled riffle crests in 2009 and 2015. The red line indicating 138mm represents the largest movable pebble diameter by an averaged length female Chinook salmon from the Elwha River (770mm ±39mm).

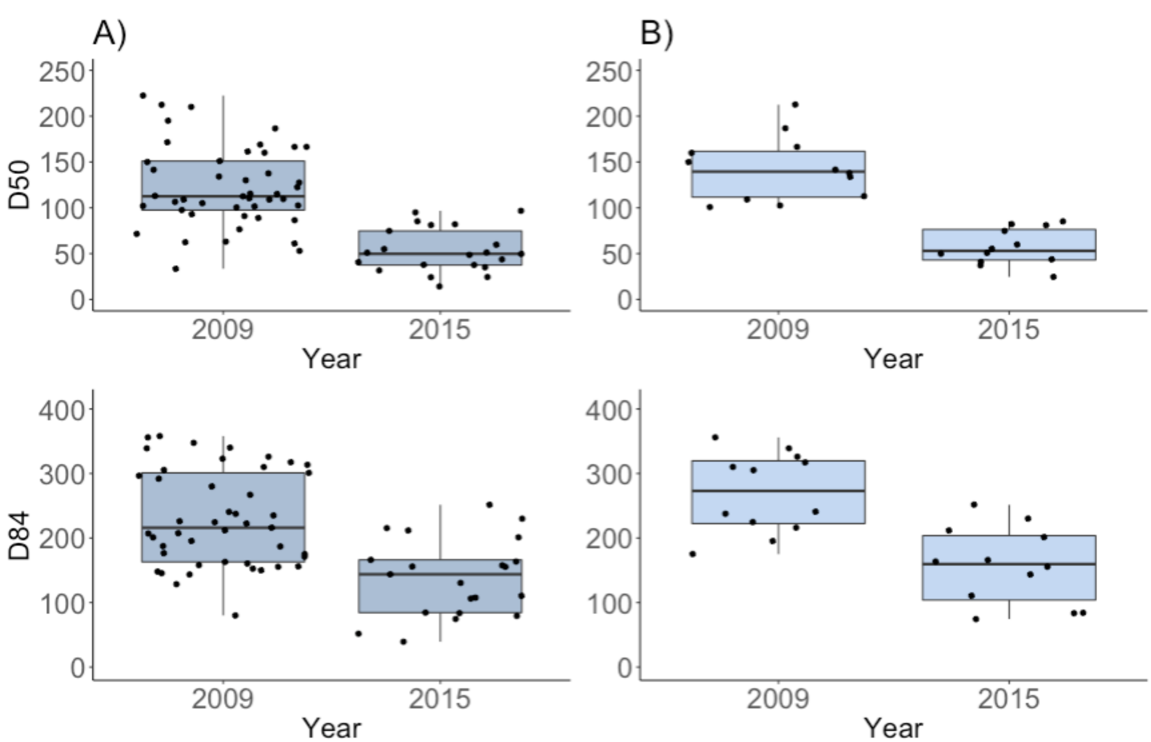

Figure 5. Median particle size (D_{50}) and D_{84} in all riffle crests sampled in the Elwha River between 2009 and 2015 (A), and in the 12 riffles that remained in the same location between both years (B).

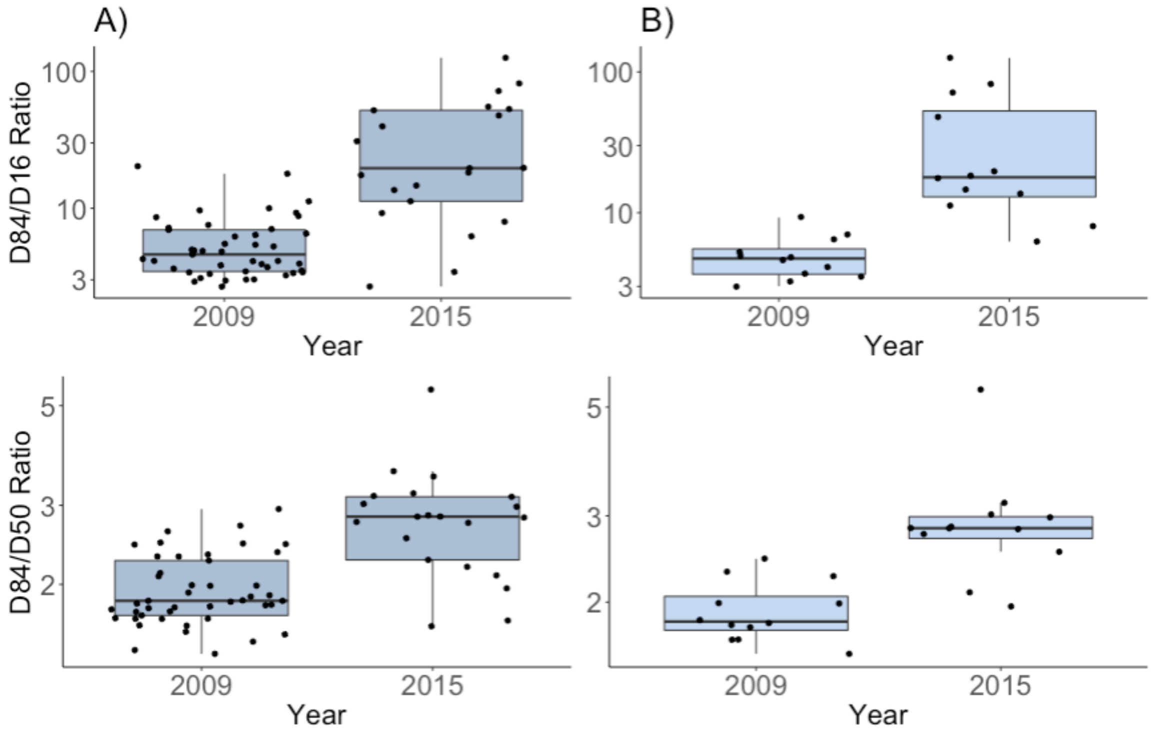

Figure 6. The distributions of the D_{84}/D_{16} and D_{84}/D_{50} ratios in all riffle crests sampled in the Elwha River between 2009 and 2015 (A), and in the 12 riffles that remained in the same location between both years (B).

Lower vs. Middle Elwha River in 2015

In the Lower Elwha River, the fraction of movable (Fm) sediment in the riffle crests was 0.88, but it was only 0.73 in the Middle Elwha River (difference = 0.15, CI [0.07, 0.24], Figure 7). Average median particle size was 28mm (CI [10, 46]) larger in the Middle Elwha River at 69mm compared to 41mm in the Lower Elwha River (Figures 8 and 9). Mean D_{84} in the Middle River was larger, averaging at 189mm compared to 101mm (difference = 88, CI [47, 127], Figures 8 and 9). Variability in particle size as described by D_{84}/D_{16} was comparable for the two river sections (Lower = 26.99, Middle = 42.01, difference=15.01, CI [17.40, 47.43], Figure 10), as was the D84/D50 ratio (Lower = 2.68, Middle = 2.99, difference = 0.31, CI[0.50, 1.12].

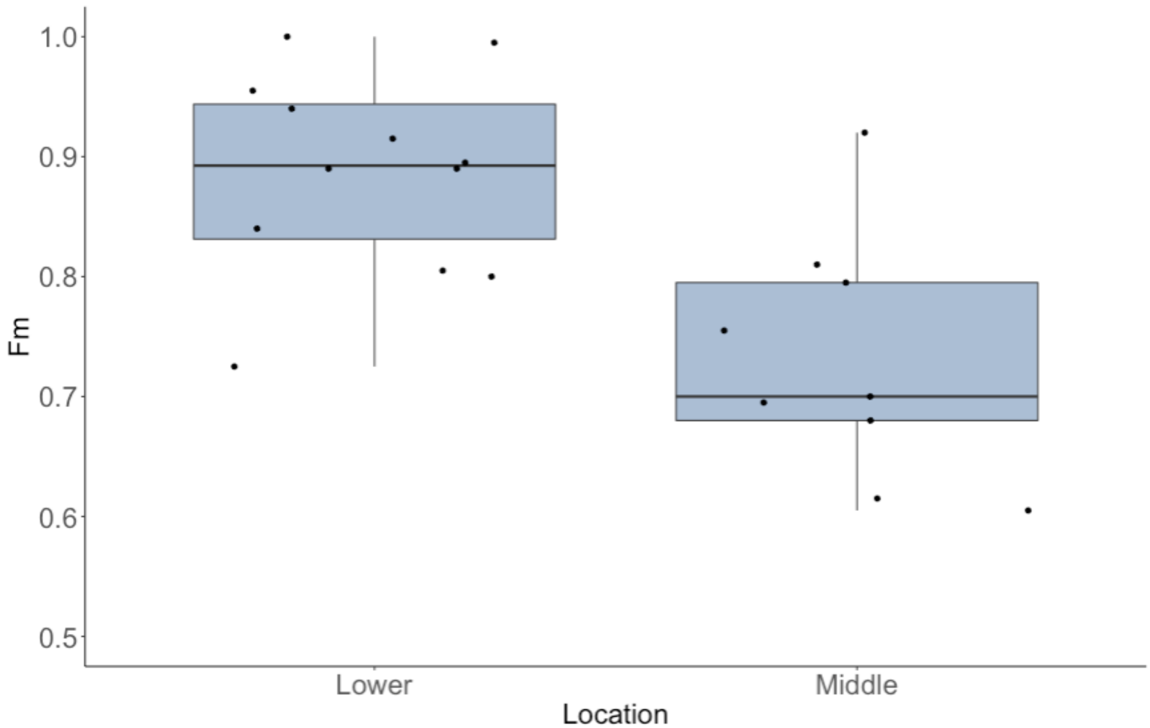

Figure 7. The distribution of the fraction of movable streambed particles (Fm) by an average length Elwha River female Chinook salmon (770mm±39mm) in the riffle crests in the Lower and Middle Elwha River in 2015.

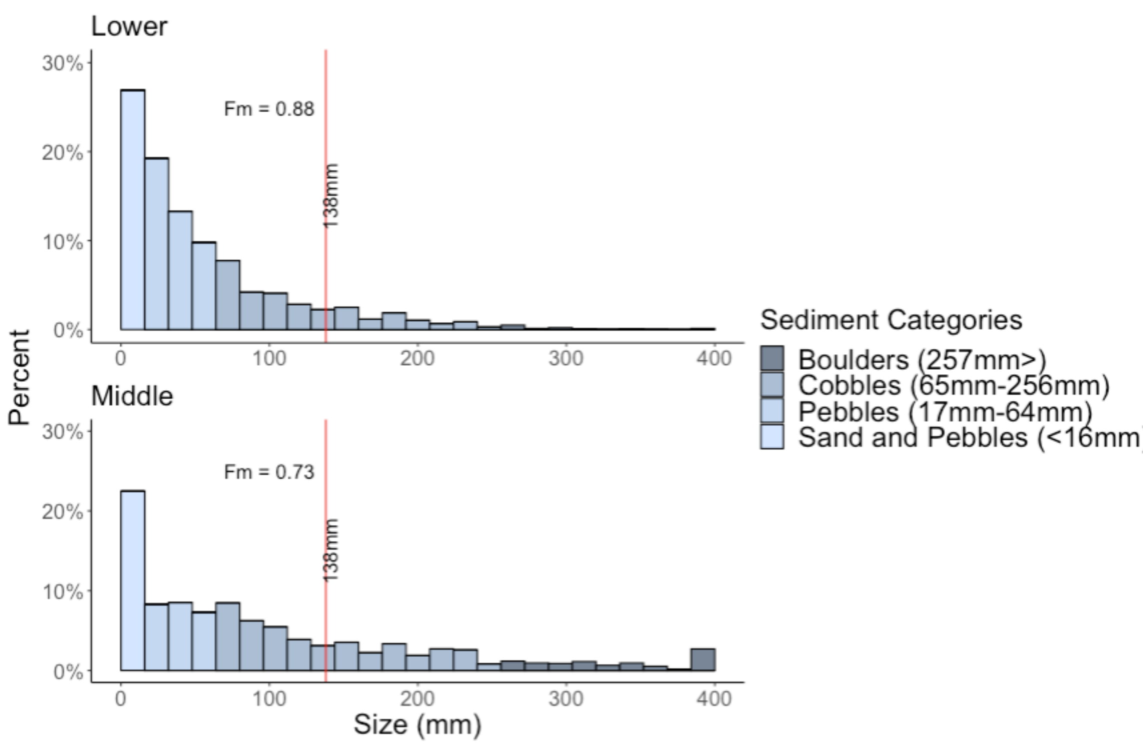

Figure 8. Pebble size distribution in all sampled riffle crests in the Lower and Middle Elwha Rivers in 2015. The red line indicating 138mm represents the largest movable pebble diameter by an averaged length female Chinook salmon from the Elwha River (770mm ±39mm).

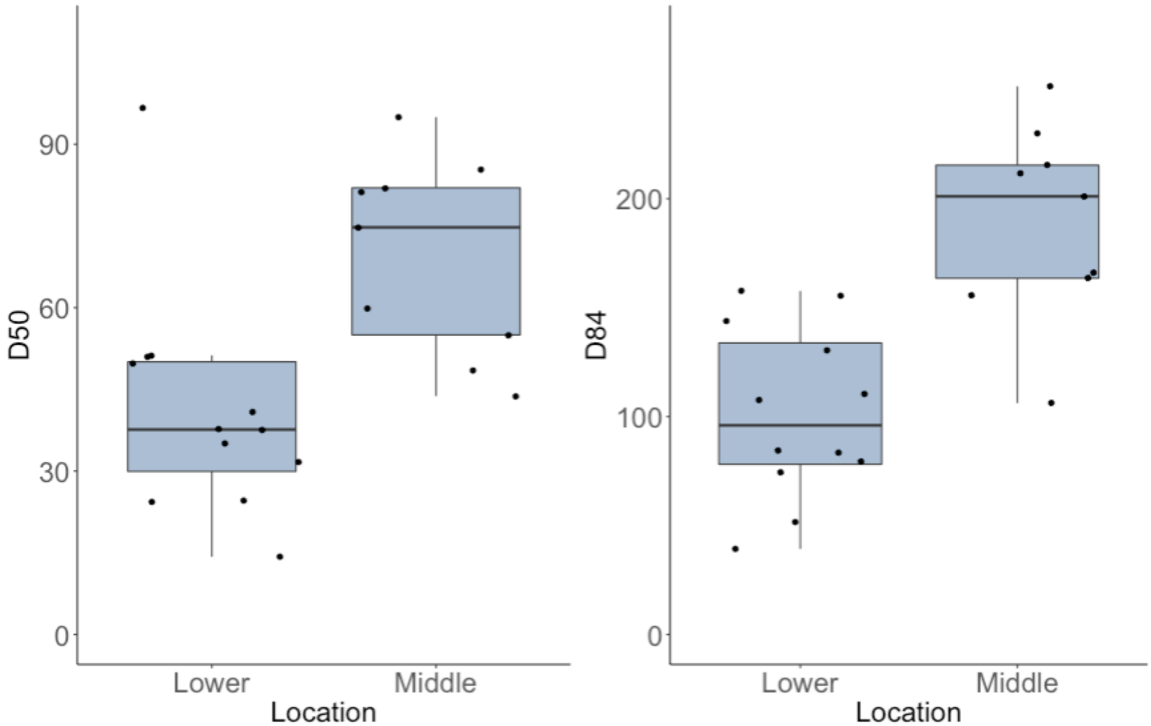

Figure 9. Median particle size (D_{50}) and D_{84} in all riffle crests sampled in the Lower and Middle Elwha in 2015.

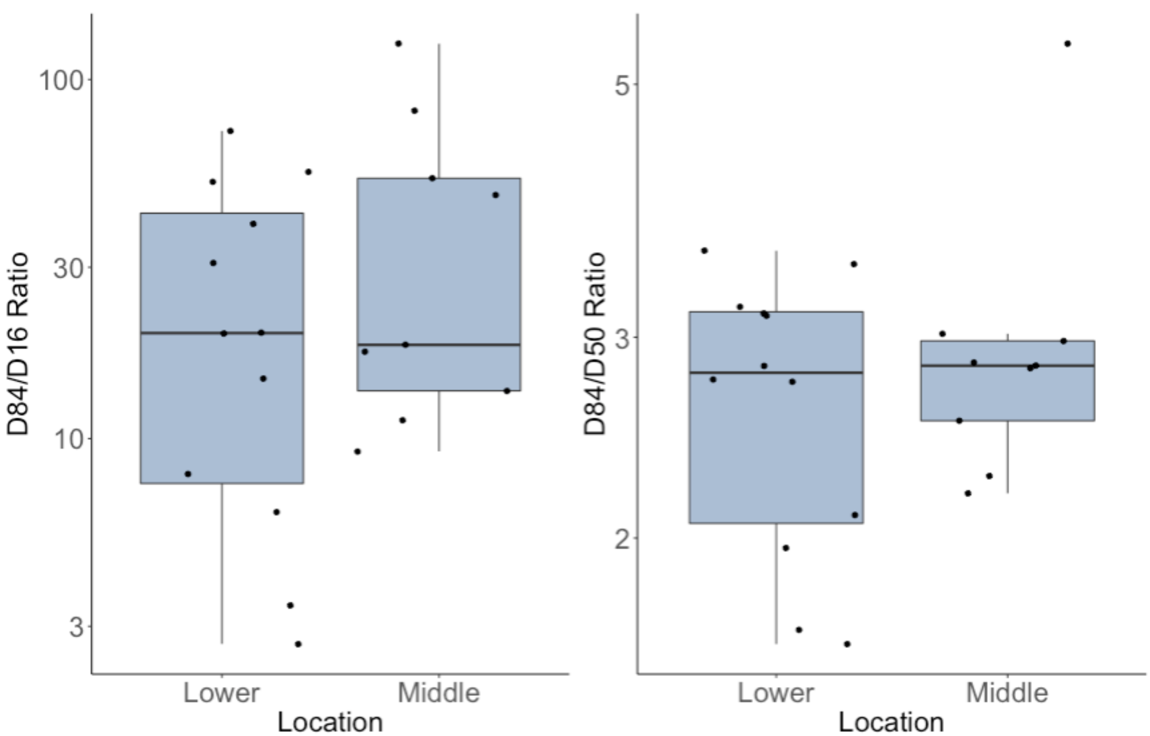

Figure 10. The distribution of the D_{84}/D_{16} and D_{84}/D_{50} ratios in all riffle crests sampled in the Lower and Middle Elwha River in 2015.

Redd Density (2015)

Redd density varied from 0.0005 to 0.05 redds per m^2, with some suggestive but weak evidence for a positive relationship with the fraction of movable particles, Fm (Figure 11). This was also the case for the change in Fm and Chinook salmon redd density (Figure 12). When comparing my results to Konrad's (2009) predicted sediment aggradation below the Elwha Dam, above the former Aldwell reservoir, and right below the Glines Canyon dam, I found few similarities. While there was a greater change in Fm below the former Elwha Dam, this was not the case above the former Aldwell reservoir or below the Glines Canyon dam. I found evidence of a slight increase in Chinook salmon redd density below where the Elwha dam was located and also above the former Aldwell reservoir, but not below the Glines Canyon dam (Figure 13).

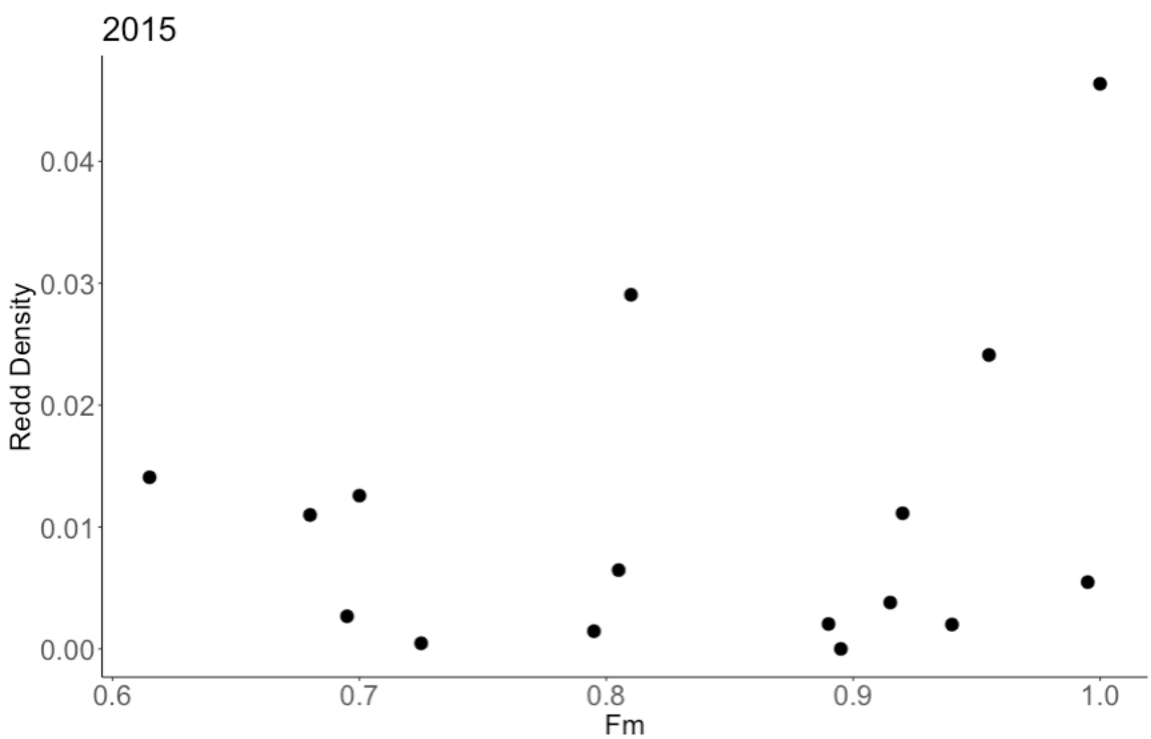

Figure 11. The relationship between the fraction of movable particles (Fm) and Chinook salmon redd density in the fifteen riffle crests that contained Chinook salmon redds in 2015.

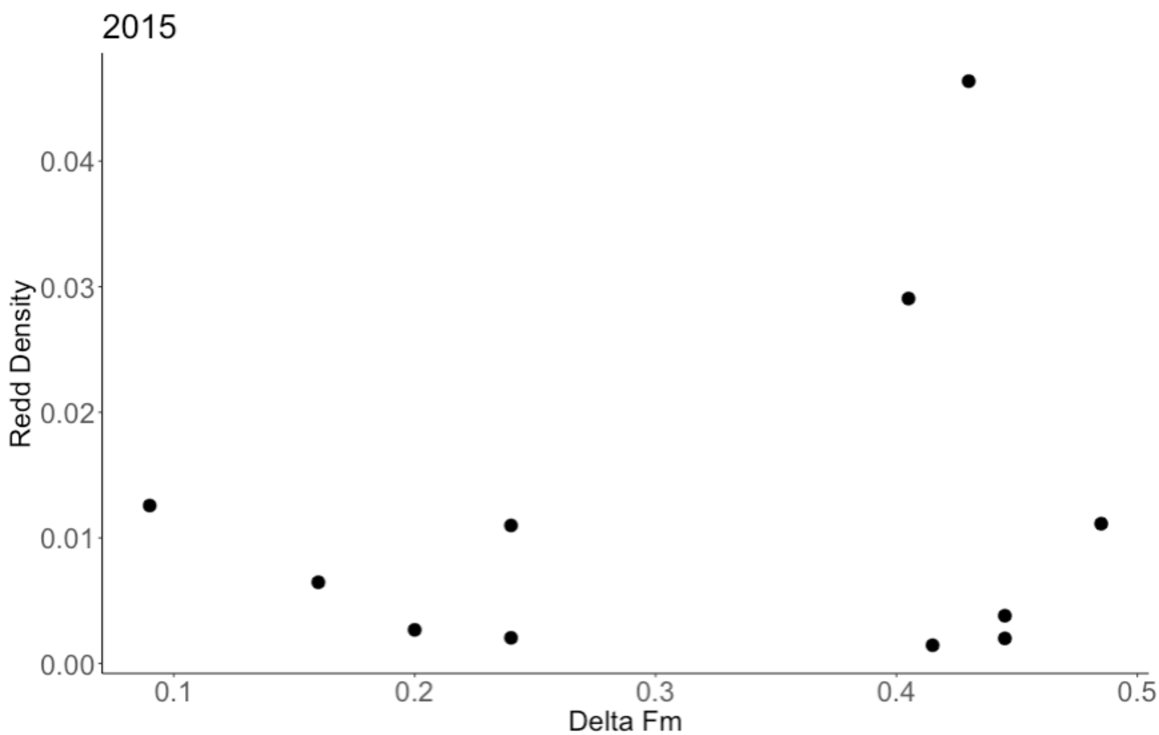

Figure 12. The relationship between the change in fraction of movable particles (Delta Fm) and redd density in eleven riffles in the Elwha River in 2015

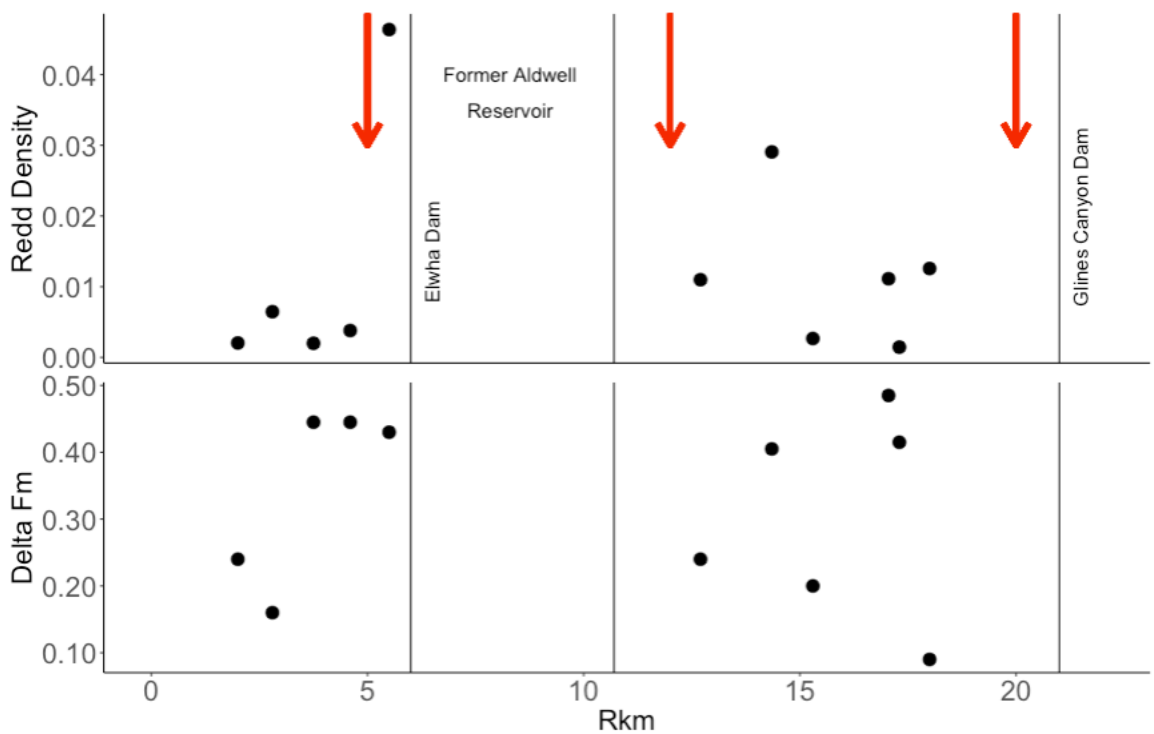

Figure 13. The relationship between river kilometer (Rkm) and redd density and the change in the fraction of movable particles (Delta Fm) in eleven riffles in the Elwha River in 2015. Red arrows indicated the locations in which Konrad (2009) modeled that sediment aggradation would occur.

Discussion

Pebble sizes decreased after dam removal resulting in more suitable spawning habitat for Chinook salmon. I expected this decrease in overall sediment size, as the Lower and Middle sections of the Elwha River were known to have fairly large, coarse substrate before dam removal and a large amount of finer sediments and small gravels were trapped above the dams (Konrad 2009). Since all riffle crests in 2009 and a large number in 2015 were surveyed, spanning much of the Middle and Lower sections of river, these results are representative of the greater habitat in these parts of the river.

The sediment ratios, D_{84}/D_{16} and D_{84}/D_{50}, indicate that there was also greater variation within the particle size distributions in the riffle crests after dam removal. The smaller ratios in 2009 resulted from a preponderance of large substrate in the pebble distributions of the riffles, whereas in 2015 there was a wider variation in sediment sizes. Although the percentage of fine sediments was higher in 2015 with potential detrimental effects on salmon eggs (Peters et al. 2017), the increased variability in particle size also resulted in a large increase in suitable spawning substrate likely mitigating any negative effects. Additionally, the greater variation in sediment size has the potential to be beneficial for both smaller and larger bodied Chinook salmon, as well as other salmonid species.

In 2015, after dam removal, the Lower Elwha River riffles had a higher proportion of smaller sediment size classes and greater potential Chinook salmon spawning capacity compared to the Middle Elwha River. Unlike in the comparison between years, however, the difference between the sediment distributions between the Lower and Middle Elwha Rivers was smaller, indicating that both sites had similar mixes of smaller and larger sediments. We expected the Lower Elwha River to have more finer sized sediments, as it was inundated by impounded sediment from both dams. Peters et al. (2017) found similar patterns of increased fines in sample sites in the Lower Elwha River in both 2013 and 2014 compared to sites in the Middle Elwha River, and this was already after the majority of sediment transport had occurred related to the dam removals (Ritchie et al. 2018).

The exploratory analysis involving Chinook salmon redd density showed interesting but ultimately inconclusive trends. I predicted higher redd densities in areas with higher proportions of particles movable by an average Elwha Chinook salmon (Fm). The lack of conclusive results in the exploratory redd density analysis emphasizes some limitations of this study. First, it is well documented that substrate size is a key factor in salmon spawning site choice, however there are several other factors that also play significant roles (Beechie et al. 2006, Harrison et al. 2017). For example, water temperature, velocity, depth, channel slope, and the behavior of salmon in relation to mates and competitors can all effect spawning location (Beechie et al. 2006). The datasets did not include any of these other variables at the riffle crest level, so their influence could not be evaluated. While it is promising that the amount of spawnable sediment increased after dam removal in the Elwha River, other habitat variables could be making some of these locations more or less favorable for Chinook salmon spawning. Including more of these variables in future dam removal studies at the riffle crest level could significantly increase our understanding of how much habitat below a dam is ideal for spawning, and which of these variables has the greatest influence on salmon spawning site selection.

Second, the spatial scale of the riffles in regards to the overall size of the Elwha River was also limiting. While some of the riffles were hundreds of square meters wide, the large size of the river meant that a significant proportion of habitat was not captured by this analysis. Changes in the riverbed, which moved or destroyed riffles during dam removal, also limited the comparative analysis. Chinook salmon redds have been counted in many areas in the Lower and Middle Elwha River that simply did not fall within the riffle crest areas. The low current abundance of the Elwha River Chinook salmon relative to historic levels and the continued expansion into the middle and upper river make interpreting patterns in redd density even more challenging. While Chinook salmon are beginning to repopulate areas that were previously above the dams, other species like coho salmon have been purposefully relocated above the dams to speed recolonization (Liermann et al. 2017). It is predicted that once Chinook salmon densities in the river begin to increase, more Chinook salmon will move further up the river into open habitat to spawn (Mapes, 2020).

Similarly, the comparison between the change in Fm and redd density, and the longitudinal exploration by Rkm in comparison with Konrad's (2009) sediment aggradation modeling was inconclusive. The greatest changes in Fm did not reflect Konrad's predicted areas of aggradation. This may indicate that the change in Fm is not an adequate proxy for aggradation. Also, a greater change in Fm is not necessarily indicative that Fm improved in these specific areas with an influx of smaller sediment. Fm may have been better in certain riffles before dam removal compared to after, despite the overall improvement of Fm that was observed throughout the riffles after dam removal. Likewise, Fm in some riffles could have been very suitable both before and after dam removal, despite no change in Fm occurring at that riffle, while other riffles with large changes may still have lower values of Fm after dam removal.

While this study has been an important first step in quantifying the impacts of sediment from the Elwha dam removals on Chinook salmon spawning habitat, future analysis could quantify these impacts for other salmonid species. Chinook salmon are the largest of the five main species, so a comparison with pink salmon (*Oncorhynchus gorbuscha*), the smallest, would allow for a better understanding of spawnable habitat suitability changed for both larger and smaller salmon species.

Conclusion

As dam removal in the United States is increasing for a variety of reasons, understanding how dams change and influence ecosystems is essential for planners and managers. In the Pacific Northwest, large dam removal for the express purpose of improving conditions for salmon has gained significant traction and public support, particularly since the 1990s (Blumm and Erickson, 2012). Four of the Klamath River Basin dams are scheduled to be removed, and the debate about removing the Lower Snake River dams for salmon remains highly contentious (Blumm and Erickson, 2012, Mapes, 2021). The Elwha River dam removals have provided a unique opportunity to quantify the impacts of a large dam removal and how salmon recovery progresses could greatly influence future decisions about dam removal.

The increased amount of habitat spawnable by Chinook salmon in the Elwha River after dam removal is encouraging with regards to the efficacy of removing dams for improving conditions for salmon. However, this is just one aspect of ecosystem recovery that managers must account for when adopting a holistic approach to assessing salmon recovery. The Elwha River is a relatively high gradient system. The movement of sediment may be quite different in lower gradient rivers. In addition, the unique location in a National Park, which protects the Elwha River from urbanization and agriculture, must also be taken into consideration when compared to other large rivers in the Pacific Northwest. Nevertheless, while each river that is under consideration for dam removal must be evaluated based on its own biotic and abiotic conditions, lessons from the Elwha River can provide managers and policymakers with a better understanding of the potential outcomes and benefits of dam removal for the purpose of restoration.

Acknowledgements

I would like to thank Dr. George Pess and Dr. Martin Liermann at NOAA for spearheading this project and for providing invaluable guidance. I also want to express my thanks and gratitude to Professor Ryan Kelly and Professor Sunny Jardine, for their support and assistance on this project and during my time at SMEA. Special thank you to Mike McHenry, Habitat Program Manager of the Lower Elwha Klallam Tribe, and Roger Peters with the United States Fish and Wildlife Service, for providing data that helped make this project possible. Finally, thank you to my family, my friends, and my SMEA cohort who have supported me throughout my life and through my studies.

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